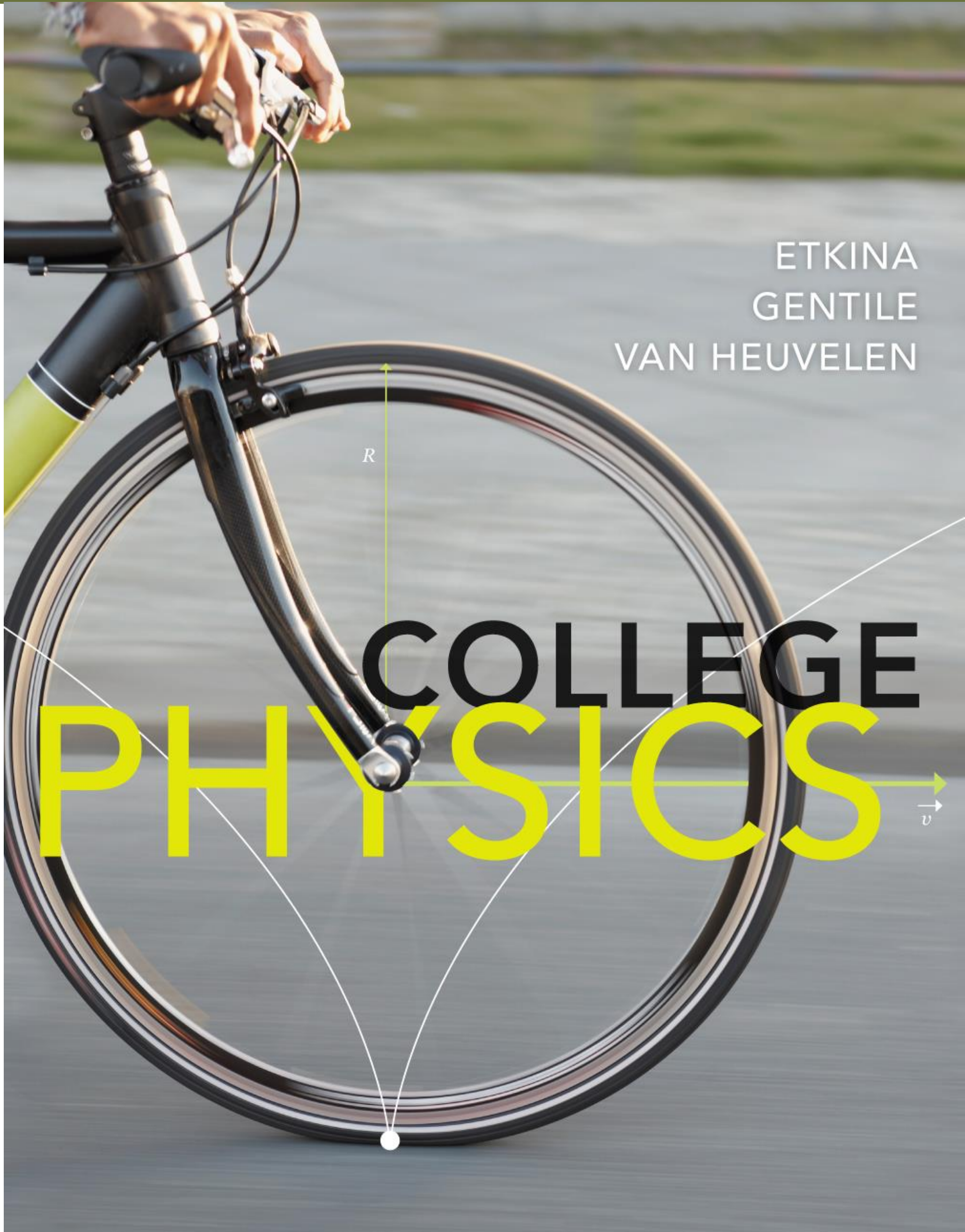
DC Circuits



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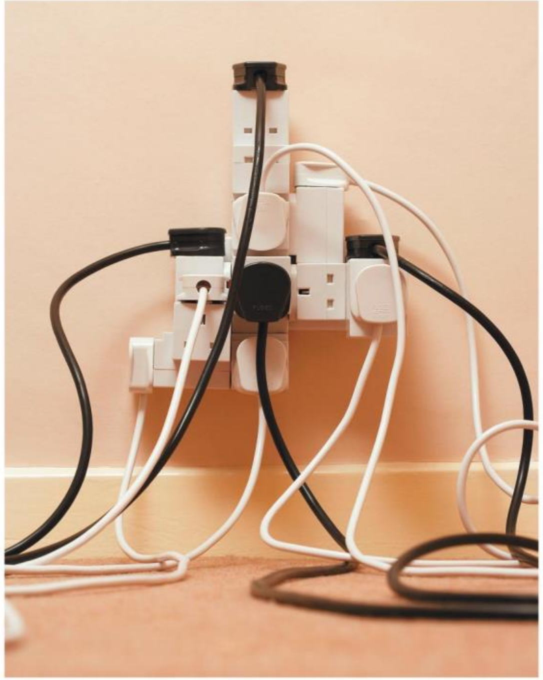
Georgetown University

DC Circuits



- Why are modern buildings equipped with electrical circuit breakers?
- How can you use an electric circuit to model the human circulatory system?
- Why is it dangerous to use a hair dryer while taking a bath?

Be sure you know how to:

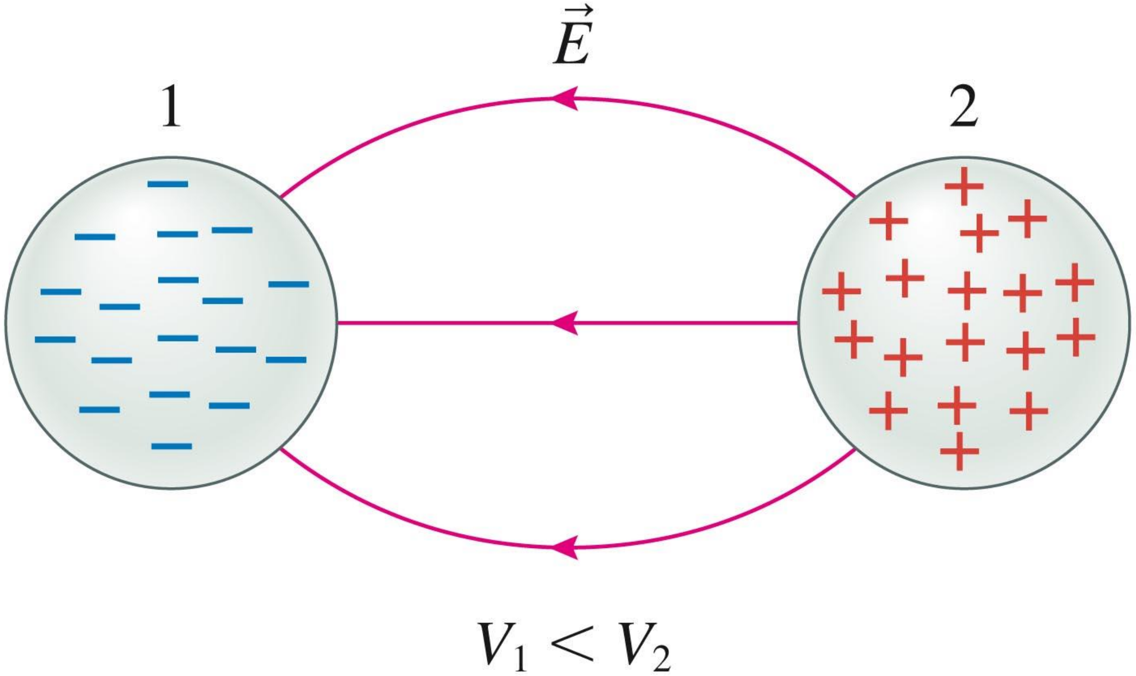
- Apply the concept of the electric field to explain electric interactions (Section 15.1).
- Define the *V* field (electric potential) and the electric potential difference ΔV (Section 15.3).
- Explain the differences in internal structure between conducting materials and nonconducting materials (Section 14.3).

What's new in this chapter

- We learned to explain processes that involved charged particles redistributing themselves: electrostatic phenomena.
  - Inside the human body's nervous system and in electric devices such as cell phones, computers, and lightbulbs, charged particles are continually moving.
- In this chapter, we learn about phenomena that involve these moving, microscopic, charged particles.

Electric current

- Cranking a Wimshurst machine's handle generates opposite charges in the two metal spheres.
- The charge separation leads to a potential difference between the spheres.

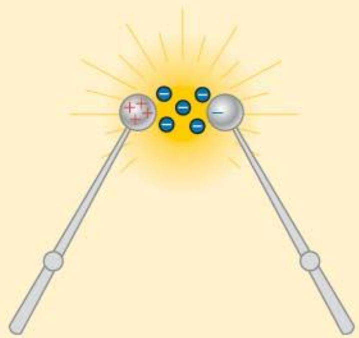
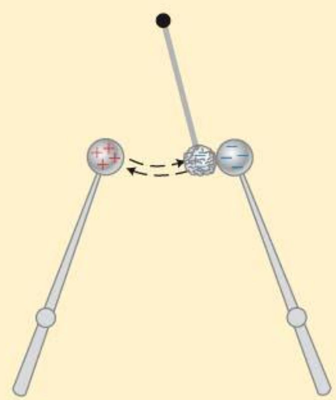


Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

16.1 **Electric potential difference and charge transfer.**

VIDEO 16.1

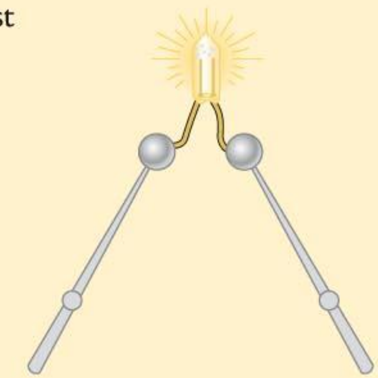
Observational experiment	Analysis
Experiment 1. Crank the handle of a Wimshurst machine and then bring the oppositely charged spheres of the machine close to each other (about 5 cm apart). You see a big spark. After the spark, when you again bring the spheres close, no more sparking occurs. 	There is charge separation and nonzero potential difference ΔV between the two spheres. The spark means that the air between the spheres becomes a conductor, leading to the rapid discharge and the production of light.
Experiment 2. Crank the handle of the Wimshurst machine and hang a light aluminum foil ball from an insulating thread between the oppositely charged spheres. The ball swings back and forth from one sphere to the other for a few minutes and then stops. If you remove the foil ball and bring the spheres near each other, no spark occurs. 	The foil ball must acquire a small amount of negative charge from the negative sphere each time it touches it. The ball carries the negative charge to the positive sphere and deposits it there and then returns to the negative sphere to repeat the process. This continues until the spheres are discharged and the potential difference between them is zero. The original electric potential energy is converted to mechanical energy and internal energy.

Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

16.1 Electric potential difference and charge transfer. *(Continued)*

VIDEO 16.1

Observational experiment	Analysis
Experiment 3. Crank the handle of the Wimshurst machine and connect the leads of a neon bulb between the charged spheres. There is a flash of light from the bulb. If you remove the bulb and bring the spheres close, no spark occurs. 	Before the bulb touches them, the spheres are charged and at different potentials. The bulb and its leads provide a conduction path to discharge the spheres. The discharge causes a flash of light from the bulb.

Patterns

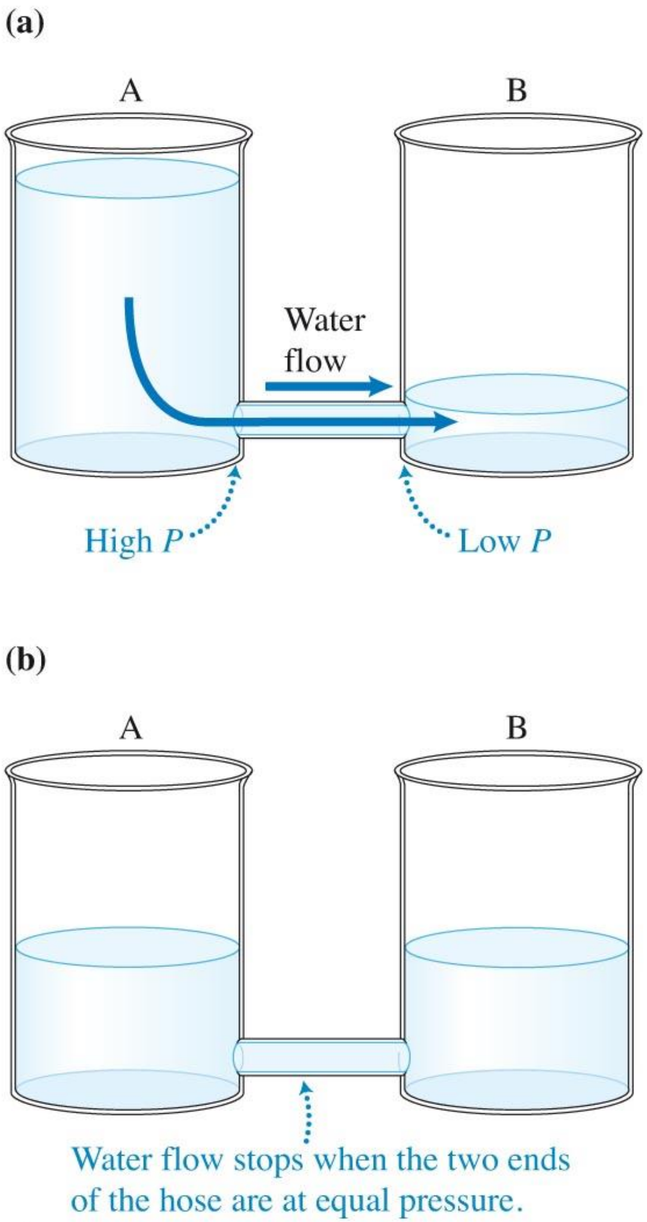
- In all three experiments, the Wimshurst machine started with negative charge on one sphere and positive charge on the other sphere. There was a potential difference ΔV between the spheres.
- This charge separation and potential difference led to a flow of charge from one sphere to the other.
- The charge flow involved different observable consequences: a spark of light, the vibrating ball of foil, or the flash of the bulb.
- After the charge flow, the Wimshurst spheres were discharged and the potential difference between them was zero. No more sparking or movement could occur.

Observation experiment outcomes

- The initial charge separation between the oppositely charged spheres allowed charge to flow between the spheres.
- The presence of a charge conduction pathway allowed charge to flow.
- The electric potential energy of the spheres was converted into some other form of energy.
- **We need to learn how to keep these processes happening continuously.**

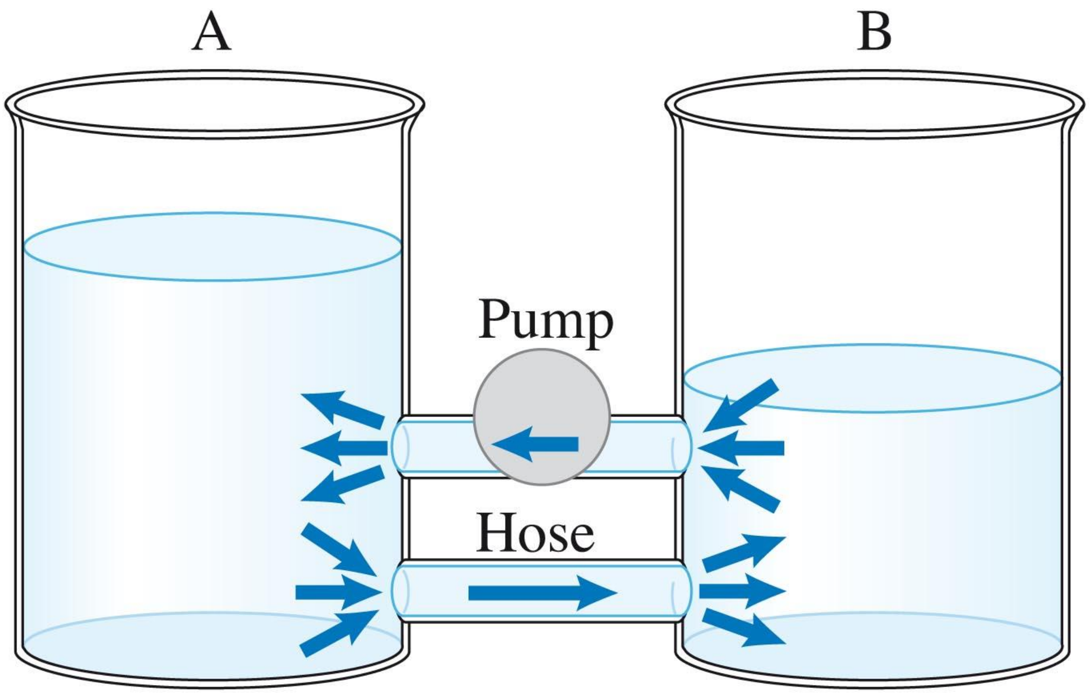
Fluid flow and charge flow

- You connect a hose between the two containers such that the two ends of the hose are at different pressures. Water starts flowing until the pressures are the same.
- The water is analogous to the excess charge on the Wimshurst spheres.



Making the process continuous

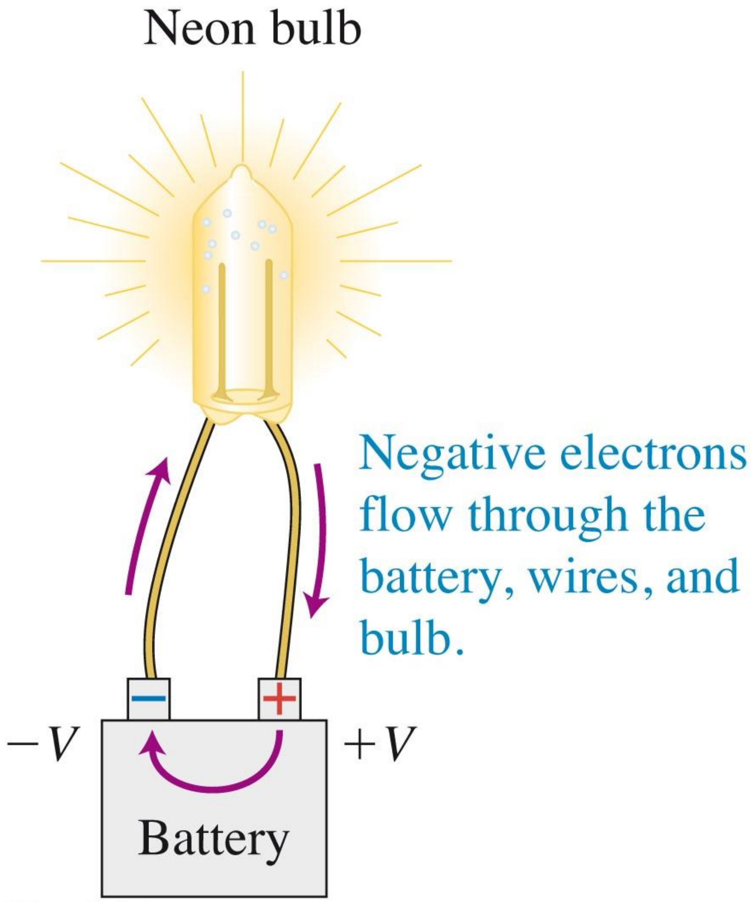
- Pumping water from B back to A maintains a pressure difference between the ends of the hose and results in a continuous flow from A to B.



The pump returns water to container A. Water flows through the hose from A back to B.

Making the process continuous

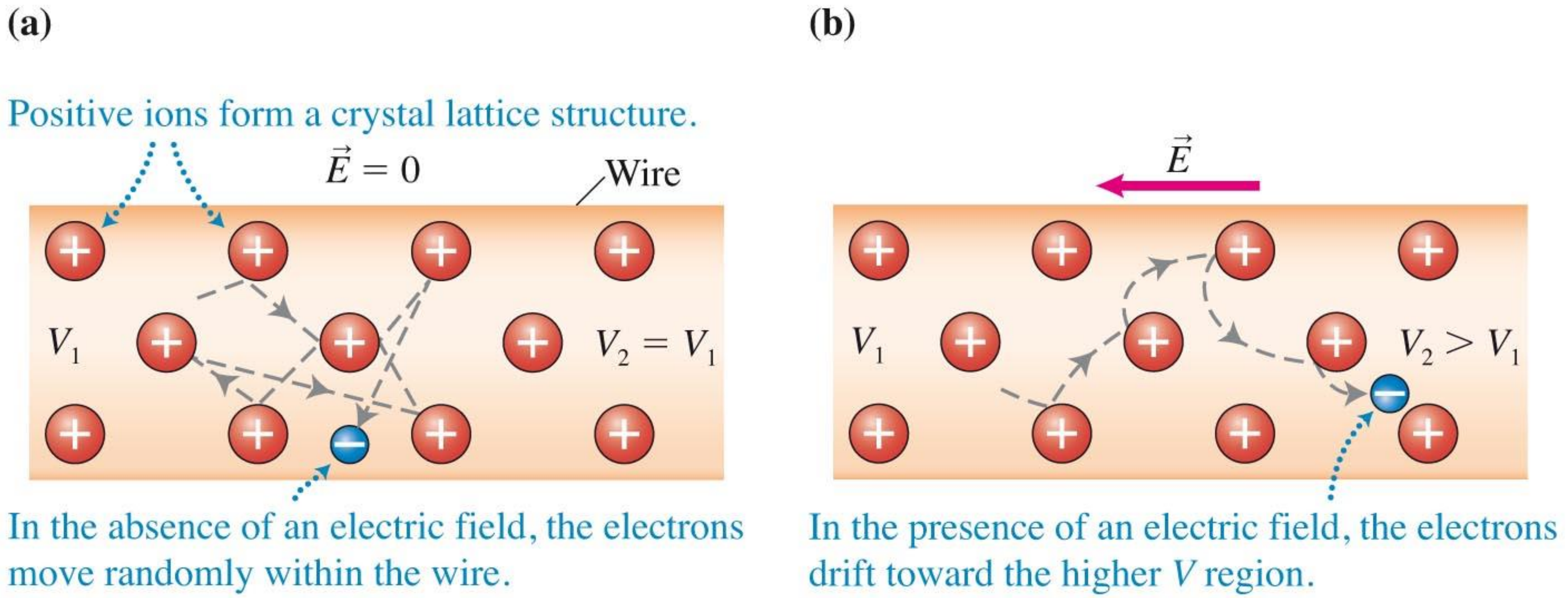
- To achieve a steady flow of electric charge, we need a device that can maintain a steady potential difference.



Electric current

- Electric current: the flow of charged particles moving through a wire between two locations that are at different electric potentials.
- Direct current: an electric current in which the charged particles move in the same direction.
- Electric circuit: a system of devices that allows for the continuous flow of charge.
- DC circuit: an electric circuit that has a direct current.

Crystal lattice model with free electrons



Drift

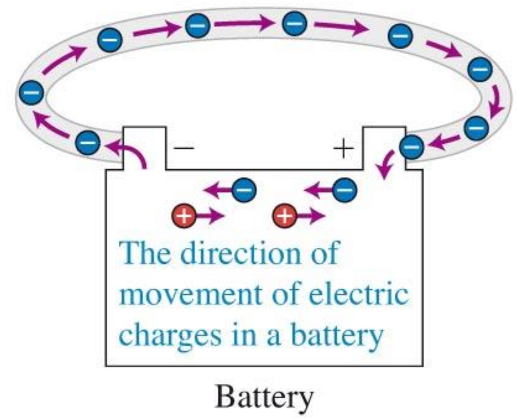
- When a wire is placed in an external electric field, the electrons accelerate in the direction opposite to the direction of the $\vec{E}$ field.
- They slow down when they "collide" with the ions.
- This drift motion occurs in the same direction for all of the electrons.

Electric current

- Free electrons in a wire drift in the direction of the higher *V* field.
- Traditionally, the direction of electric current in a circuit is defined as opposite to the direction of the electrons' drifting motion.

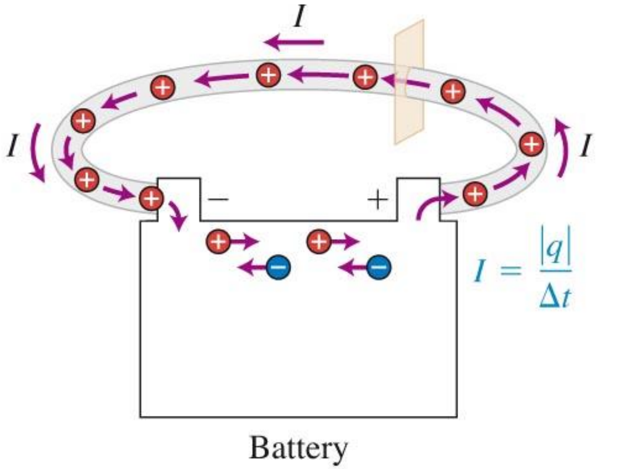
(a)

Electrons travel around the circuit toward the positive terminal.



(b)

The electric current *I* is defined in terms of the direction in which positive charges would move.



Electric current

Electric current The magnitude of the physical quantity of electric current I in a wire equals the magnitude of the electric charge q that passes through a cross section of the wire divided by the time interval Δt needed for that amount of charge to pass:

$$I = \frac{|q|}{\Delta t} \tag{16.1}$$

The unit of current is the **ampere** A, equivalent to one coulomb per second C/s. A current of 1 A (one ampere, or amp) means that 1 C of charge passes through a cross section of the wire every second. The direction of the current is in the direction positive charges would move.

In SI units, the unit for electric current is a fundamental unit. The unit of electric charge (1 coulomb) is defined in terms of the ampere as $1\text{ C} = (1\text{A})(1\text{ s})$. In the next chapter, we study the phenomenon that can be used to define the ampere.

Quantitative Exercise 16.1

- Each second, 1.0×10^{17} electrons pass from right to left past a cross section of a wire connecting the two terminals of a battery. Determine the magnitude and direction of the electric current in the wire.

Batteries and emf

Emf ε The emf ε equals the work W done by a battery per coulomb of electric charge q that is moved through the battery from one terminal to the other in order to maintain a potential difference at the battery terminals:

$$\varepsilon = \frac{W}{q} \tag{16.2}$$

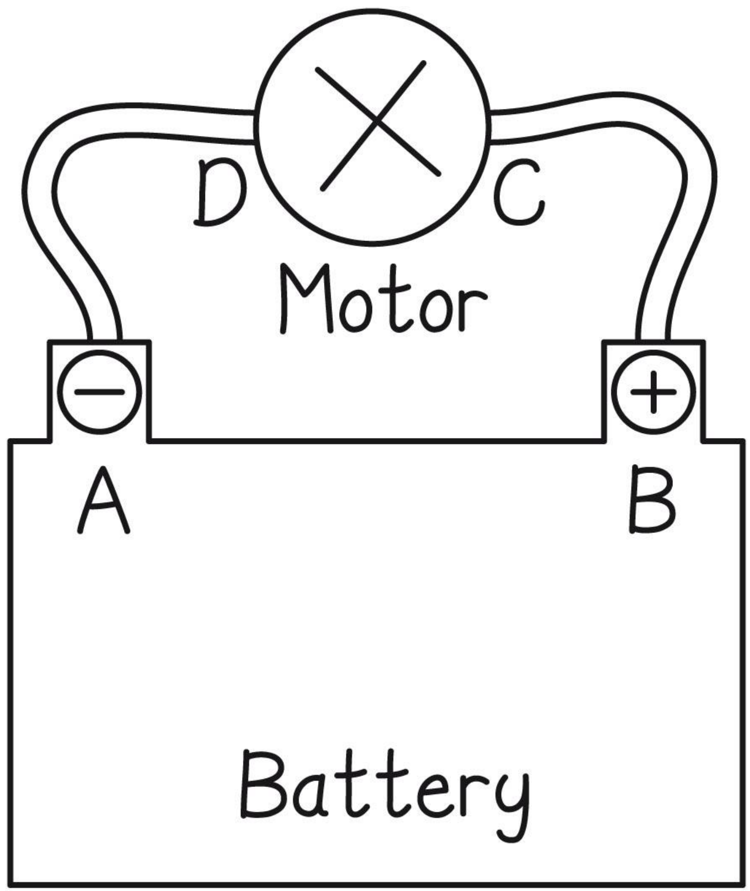
- The physical size of a battery is not related to the emf but to its storage capacity—the total charge it can move before it must be replaced or recharged.

The language of physics: Force and work

The language of physics: Force and work Electromotive force (emf), despite its name, is not a force. Emf is work done per coulomb of charge. The term *electromotive force* was coined by Alessandro Volta (1745–1827), who invented the battery. At that time the terms "force," "energy, " and "power" were used somewhat interchangeably. The linguistic distinction between force and energy had not yet been made clear. For example, kinetic energy was called "live force" and potential energy was called "dead force."

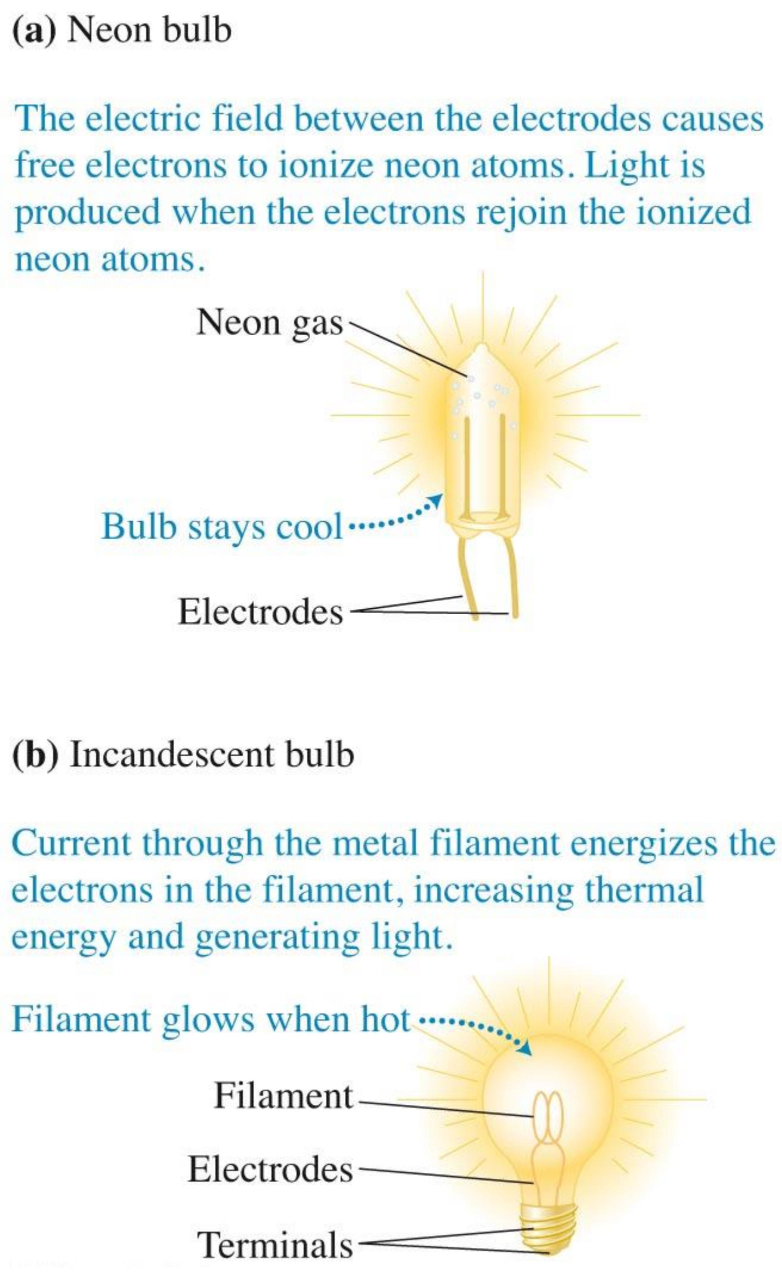
Conceptual Exercise 16.2

- You connect a 9.0-V battery to a small motor. Describe the changes in electric potential in the circuit with a graph.



Neon and incandescent bulbs

- A neon bulb consists of a glass bulb filled with low-pressure neon gas.
- An incandescent bulb has a metal filament inside it.

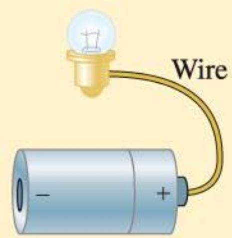


Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

16.2 **Making a flashlight bulb glow.**

VIDEO 16.2

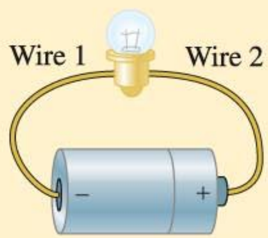
Observational experiment	Analysis
Connection 1—No light is produced. 	A wire connects one bulb terminal to one battery terminal.
Connection 2—no light 	Both bulb terminals are connected to the same battery terminal with a wire.

Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

16.2 Making a flashlight bulb glow. *(Continued)*

VIDEO 16.2

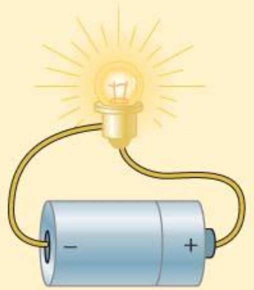
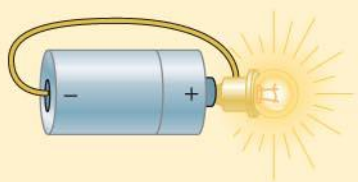
Observational experiment	Analysis
Connection 3—no light 	One bulb terminal is connected to both battery terminals with wires.
Connection 4—light 	The two bulb terminals are connected to the two battery terminals with wires.

Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

16.2 **Making a flashlight bulb glow.** *(Continued)*

VIDEO 16.2

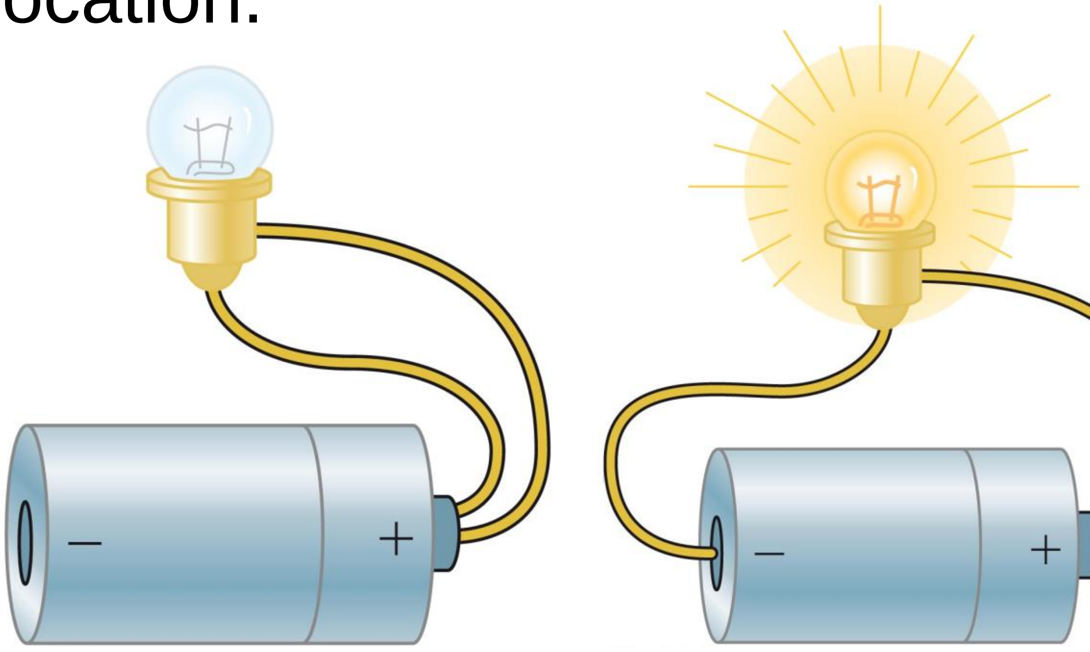
Observational experiment	Analysis
Connection 5—light 	The same as connection 4, only the bulb terminals are connected to opposite battery terminals.
Connection 6—light 	The same as connection 4, only one bulb terminal is directly touching the battery.

Pattern

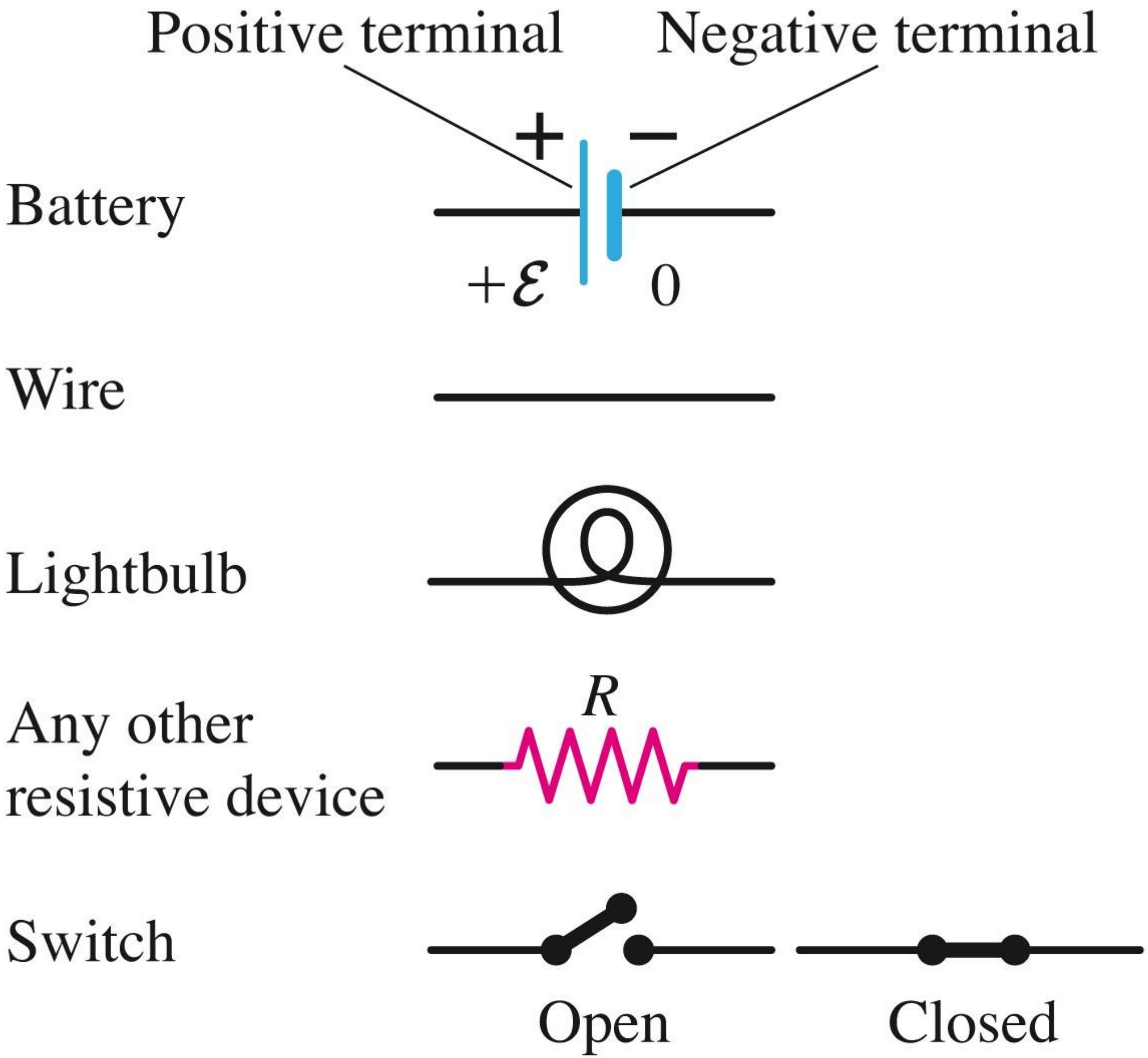
The incandescent bulb glows if one battery terminal is connected to one lightbulb terminal and the other battery terminal is connected to the other bulb terminal either with a metal wire or by direct contact. This arrangement is an example of a **complete circuit**.

Complete circuits

- To check whether any circuit you build is complete, trace the path of an imaginary positive charge moving from the positive terminal of the battery to the negative terminal.
- The path must pass along conducting material at every location.

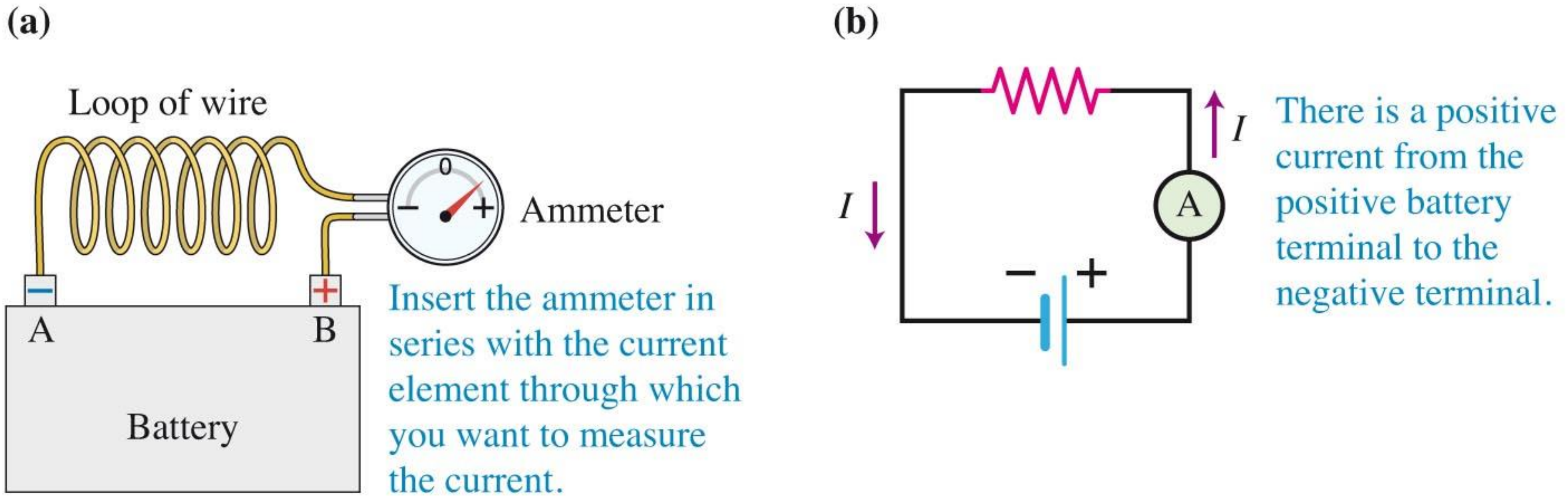


Symbols for the elements in electric circuits



Ammeters

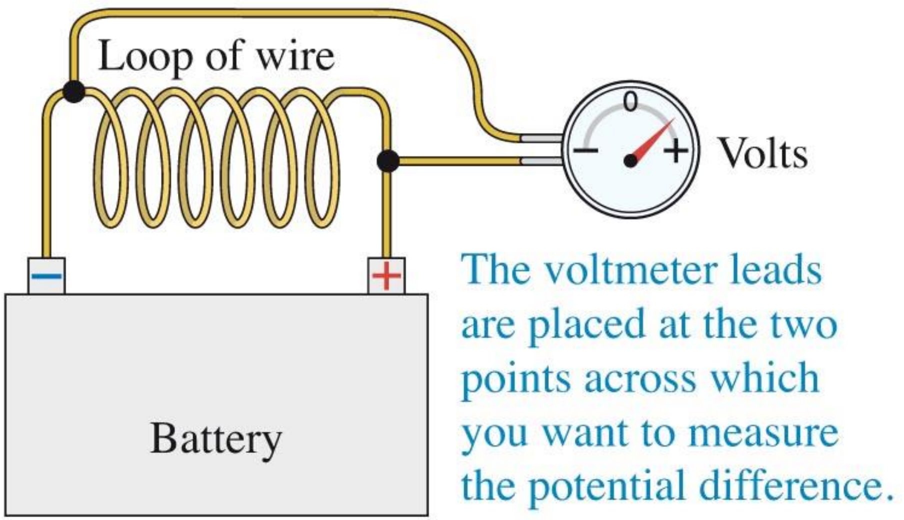
- An ammeter acts like a water flow meter.
  - If you wish to measure how much water flows through a cross section of a pipe, the water must pass through the flow meter.



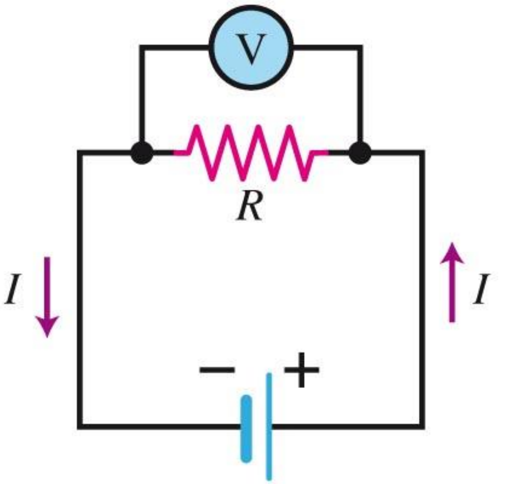
Voltmeters

- A voltmeter measures the electric potential difference between two points in a circuit.
  - Using a voltmeter is analogous to using a pressure meter to measure the water pressure difference.

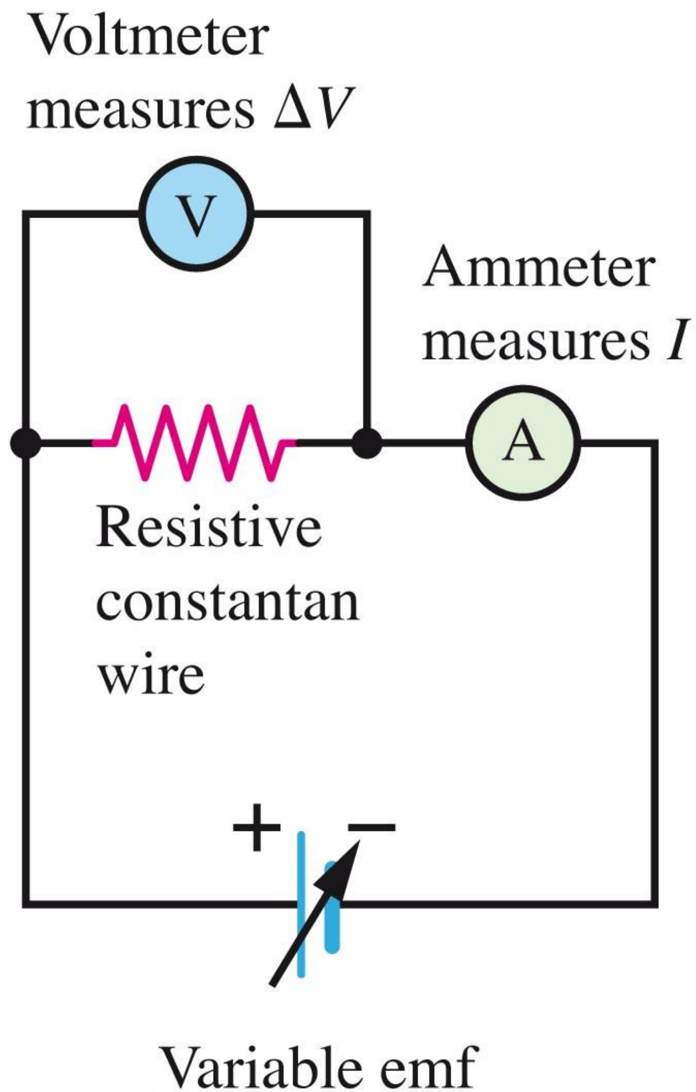
(a)



(b)



Measuring current through and potential difference across a resistive wire



Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

16.3 Developing a relationship between current through and potential difference across a resistive element.

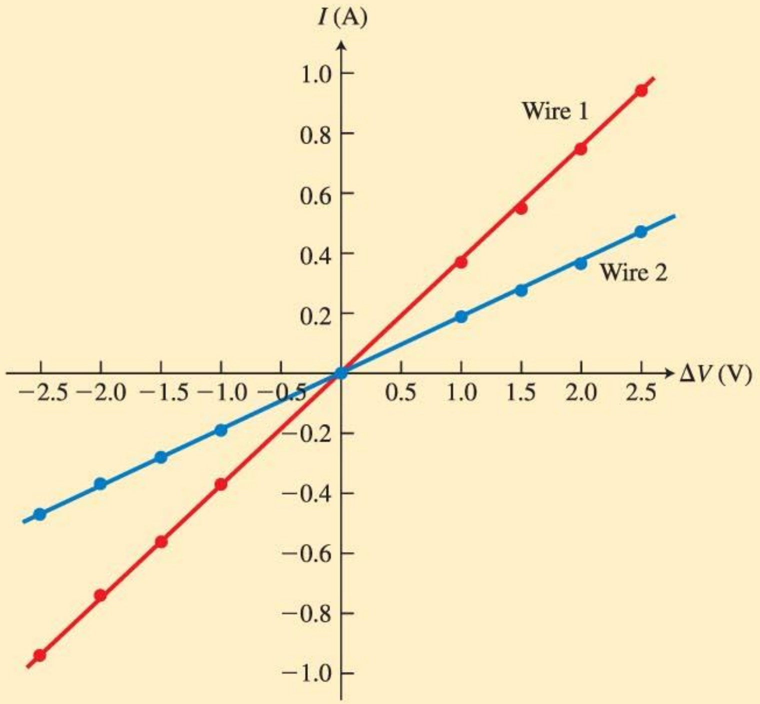
Observational experiment	Analysis			
The electric circuit is shown in Figure 16.12. By changing the setting of the variable emf, we vary the potential difference ΔV across the ends of the constantan resistive wire and measure the current I through it. Then we repeat the experiment using a constantan wire of different length. Finally, we graph the results.	**Wire 1 potential difference ΔV (volts)**	**Wire 1 current I (amps)**	**Wire 2 potential difference ΔV (volts)**	**Wire 2 current I (amps)**
	0	0.00	0	0.00
	1.0	0.37	1.0	0.19
	1.5	0.56	1.5	0.28
	2.0	0.74	2.0	0.37
	2.5	0.94	2.5	0.47
	−1.0	−0.37	−1.0	−0.19
	−1.5	−0.56	−1.5	−0.28
	−2.0	−0.74	−2.0	−0.37
	−2.5	−0.94	−2.5	−0.47

Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

16.3 Developing a relationship between current through and potential difference across a resistive element. *(Continued)*

Observational experiment	Analysis
	The graphs I versus ΔV for both resistive wires are straight lines that pass through the origin.



Pattern

The graphs show that the current through both resistive wires is directly proportional to the potential difference across them. When the potential difference reverses direction, so does the current. The slopes of the lines are different for different resistive wires.

Relationship between current and electric potential difference

- The larger the potential difference across the wire, the larger the $\vec{E}$ field inside.
- When a larger electric force is exerted on the electrons, it results in larger accelerations of the electrons between the collisions with the ions in the lattice and, therefore, a larger current through the wire.

Resistance

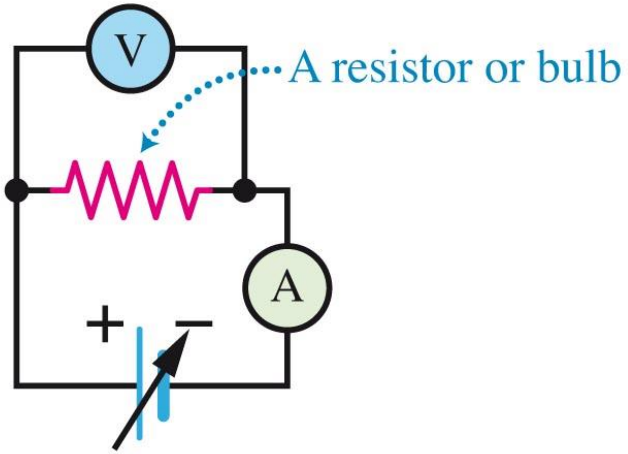
- Resistance characterizes the degree to which an object resists a current.
- We can write the relationship between current and potential difference using resistance *R*:

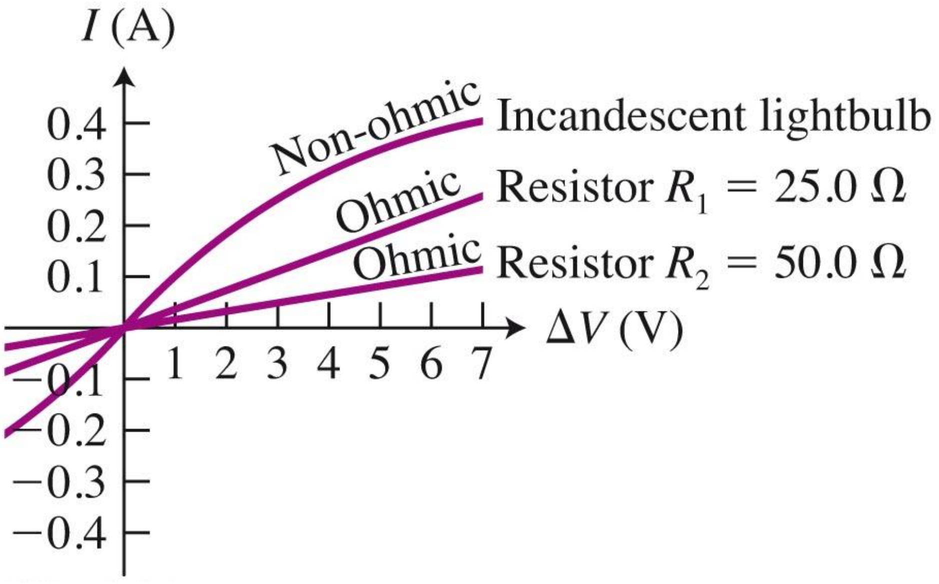
$$I = \frac{\Delta V}{R}$$

- The unit of resistance is called the ohm; 1 ohm = 1 volt/ampere.

Ohmic and non-ohmic circuit elements

- If the resistance of a circuit element does not depend on the potential difference across it, the element is called ohmic.
- Circuit elements that cannot be modeled as ohmic devices are called non-ohmic.





Ohm's law

Ohm's law The current I through a circuit element (other than a battery) can be determined by dividing the potential difference ΔV across the circuit element by its resistance R:

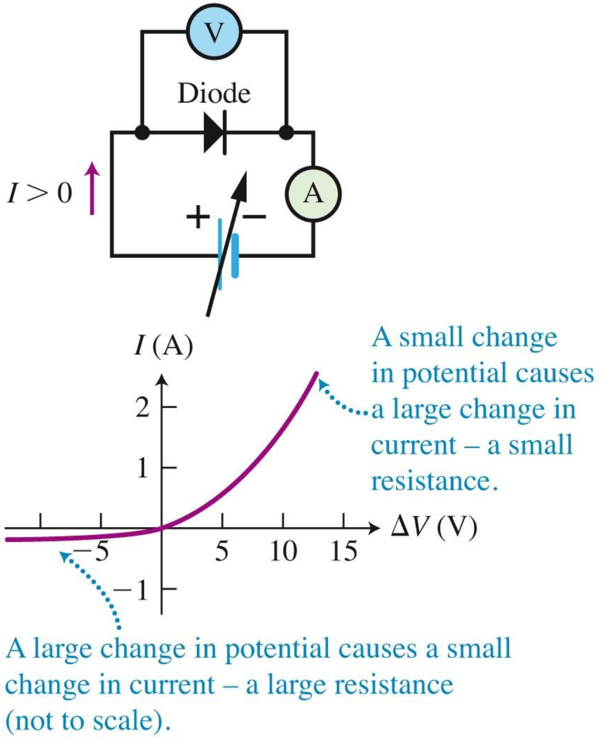
$$I = \frac{\Delta V}{R} \tag{16.3}$$

Tip

TIP Note that ΔV is the potential difference between one side of the device and the other (hence the Δ), whereas current I is the flow rate of charge through the device.

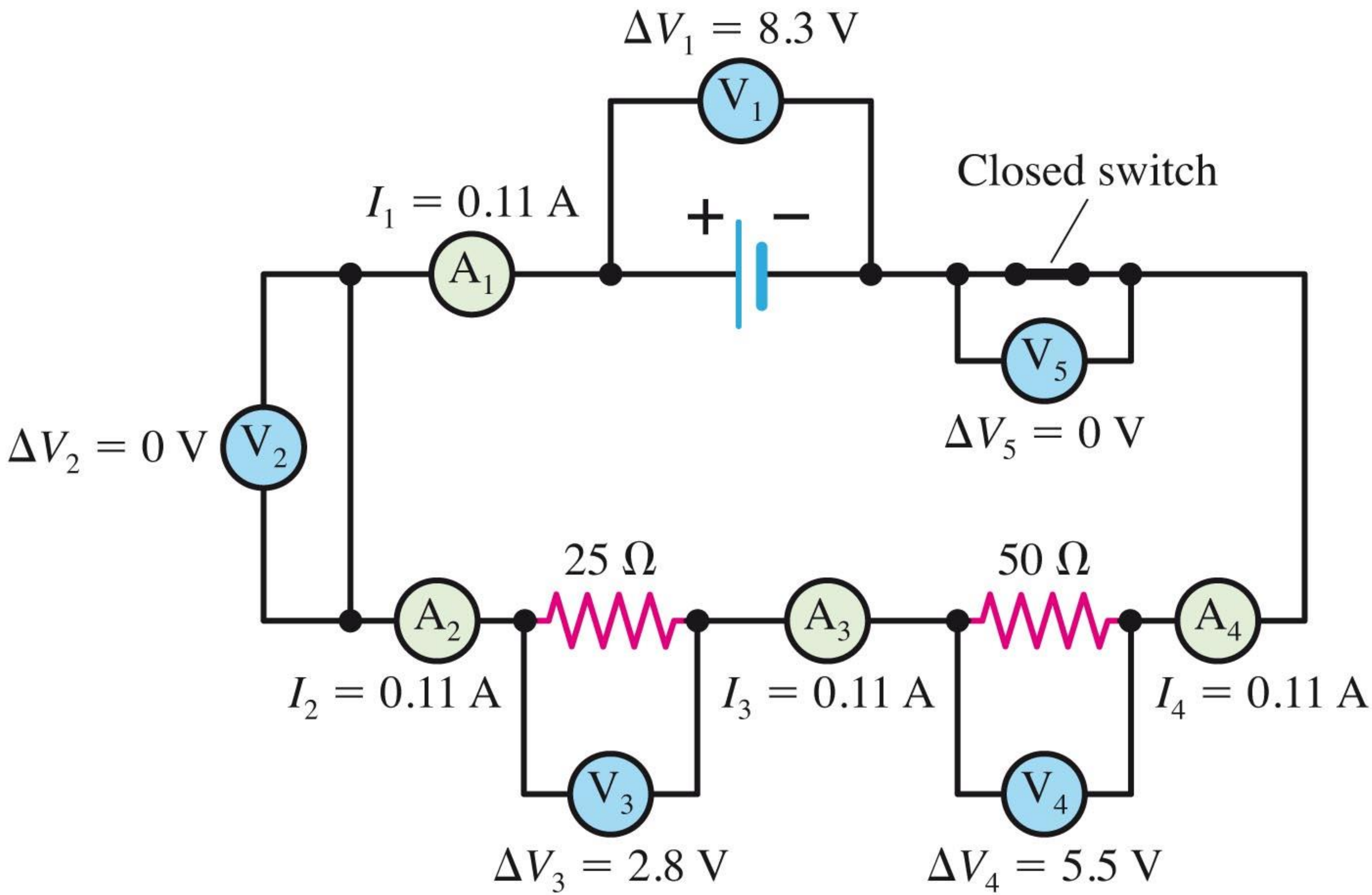
Diode

- A diode is a non-ohmic circuit element that consists of two kinds of materials that cause it to be asymmetrical with respect to the potential difference across it.



- Using a diode in a circuit allows you to achieve one-directional current.

Testing Ohm's law



Testing experiment

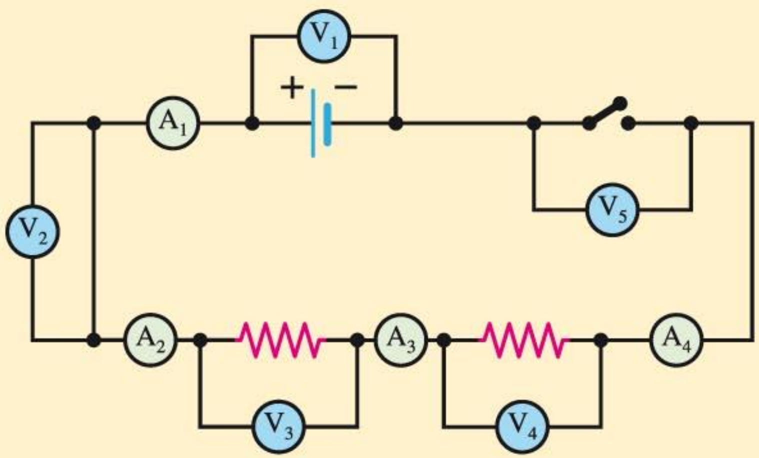
TESTING EXPERIMENT TABLE

16.4 Applying Ohm's law to an open circuit.

VIDEO 16.4

Testing experiment

Use the same circuit as in Figure 16.15, only this time with the switch open.



Prediction

We predict that the current in the circuit is zero, the ammeters will measure zero current $I = 0$, and according to Ohm's law, voltmeters 2–5 will measure zero potential difference $\Delta V = IR = 0R = 0$.

Outcome

Ammeter readings		Voltmeter readings	
Ammeter 1	0 A	Voltmeter 1	8.5 V
Ammeter 2	0 A	Voltmeter 2	0 V
Ammeter 3	0 A	Voltmeter 3	0 V
Ammeter 4	0 A	Voltmeter 4	0 V
		Voltmeter 5	8.5 V

Conclusion

We predicted 0 for voltmeter 5, but it measured 8.5 V. The outcome of the experiment does not match the prediction. We need to either revise Ohm's law or examine how we apply it.

Testing experiment outcome

- When the prediction and the outcome do not match, we need to reevaluate our reasoning.
  - In an open switch, we cannot apply relation $\Delta V = IR$, as we do not know the result of multiplying zero by infinity.
  - When a switch is open, the whole part of the circuit connected to the positive terminal of the battery is at a potential of that terminal. The part of the circuit connected to the negative battery terminal is at a potential of 0.0 V.

Tip

TIP A burned out lightbulb causes the current in the line with the bulb to be zero. It is like an open switch. If the light switch on the wall is on, there may be a 120-V potential difference across the contact points in the bulb canister. It is not safe to touch the contact points!

Quantitative Exercise 16.3

- When commercial resistor 1 is connected to a 9-V battery, the current through the resistor is 0.1 A. When commercial resistor 2 is connected to the same battery, the current through it is 0.3 A.
  1. What can you learn about the resistors?
  2. Which assumptions did you make?

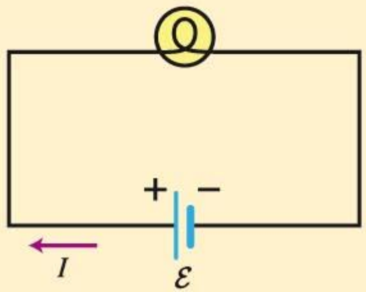
Observational experiment

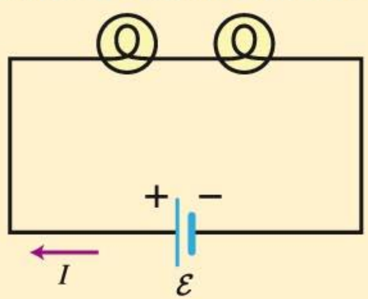
OBSERVATIONAL EXPERIMENT TABLE

16.5 **Multiple bulbs arranged in series.**

VIDEO 16.5

Observational experiment	Analysis
Experiment 1. One bulb connected to a battery is bright.	The lightbulb is lit when the circuit is complete.
Experiment 2. Two bulbs connected one after the other (in series) to the battery from Experiment 1 are each dimmer than the bulb in 1 but have the same brightness as each other. The bulbs are of equal brightness but dimmer than in experiment 1.	■ There must be less current through the bulbs than in Experiment 1. ■ Each bulb must have the same lower current through it (since they are equally bright).





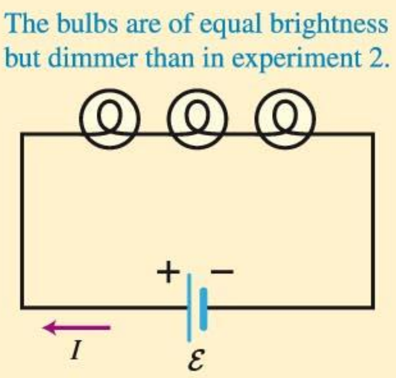
Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

16.5 **Multiple bulbs arranged in series.** ***(Continued)***

VIDEO 16.5

Observational experiment	Analysis
Experiment 3. Three bulbs connected in series to the same battery are each dimmer than the bulbs in Experiments 1 and 2 but have the same brightness as each other.	■ There must be less current through the bulbs than in Experiments 1 and 2. ■ Each bulb must have the same even lower current through it (since they are equally bright.)

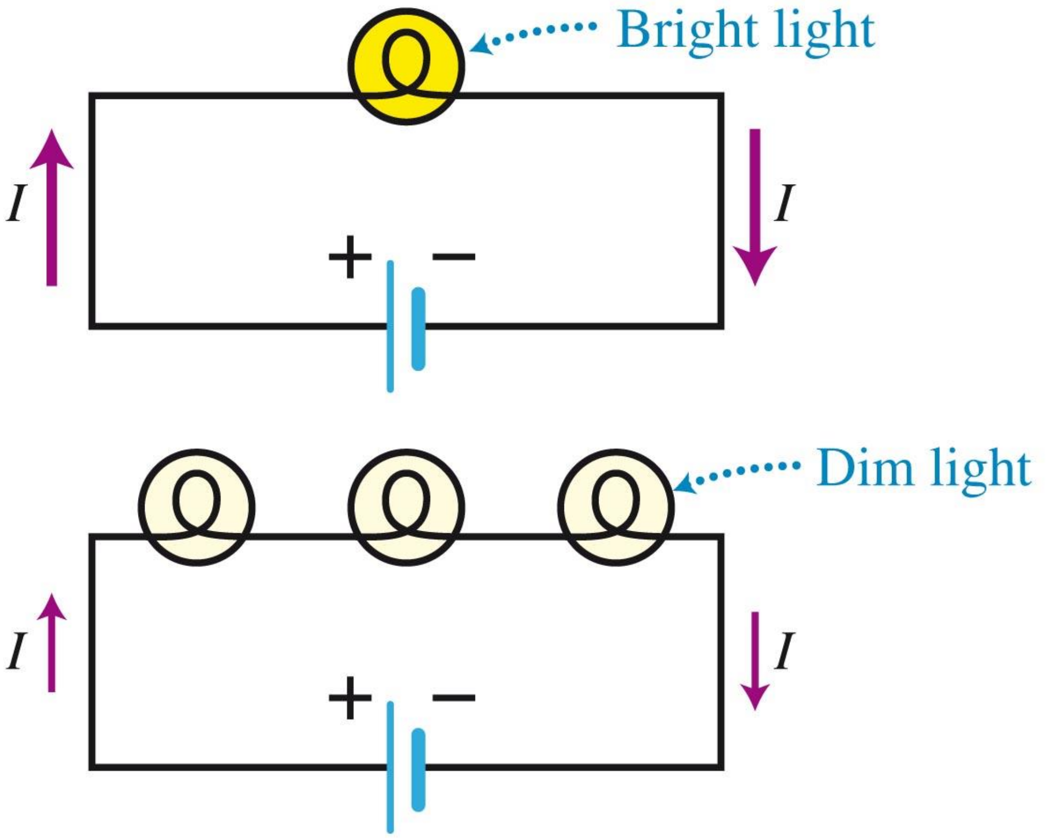


Patterns

- The brightness of all identical bulbs arranged in series is the same.
- Adding more bulbs arranged in series decreases the brightness of all bulbs.

Circuits in series

- Adding more bulbs must increase the resistance of the circuit, reducing the electric current everywhere in the circuit.
- A battery is not a source of constant current.



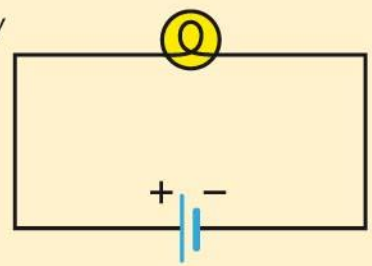
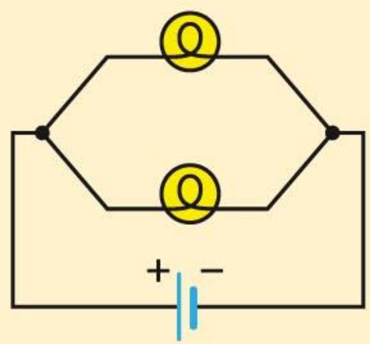
With more bulbs in series, there is less current and the bulbs are dimmer.

Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

16.6 **Multiple bulbs arranged in parallel.**

VIDEO 16.6

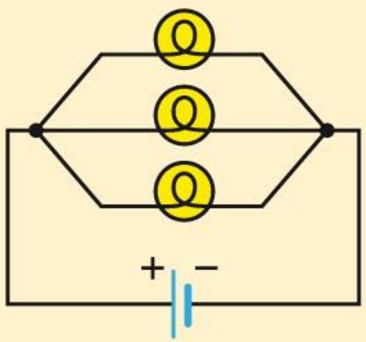
Observational experiment	Analysis
Experiment 1. One bulb connected to a battery is bright. 	The bulb is lit when the circuit is complete.
Experiment 2. Two identical bulbs connected in parallel to the same battery are as bright as the bulb in Experiment 1 and the same brightness as each other. 	Since both bulbs have the same brightness, they must have an equal current through them.

Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

16.6 Multiple bulbs arranged in parallel. ***(Continued)***

VIDEO 16.6

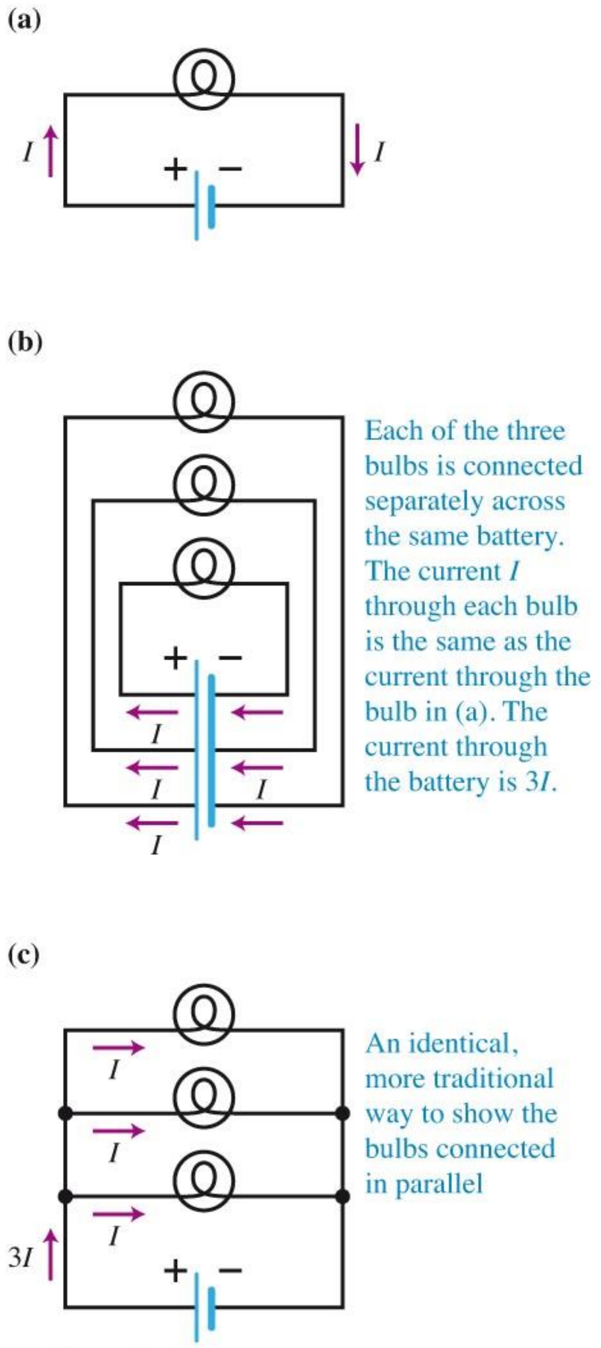
Observational experiment	Analysis
Experiment 3. Three identical bulbs connected in parallel to the same battery are as bright as the bulbs in Experiments 1 and 2 and the same brightness as each other. 	There must be an equal current through each bulb in every experiment, even when additional bulbs are added.

Pattern

The brightness appears to be the same in all of the identical bulbs in parallel and is not affected by the presence of the other bulbs.

Circuits in parallel

- For each identical bulb to be equally bright and have the same brightness as a single bulb, the current must be the same through all of the bulbs.



Qualitative investigations of electric circuits

- When circuit elements are connected in series, the current through each element is the same.
- When circuit elements are connected in parallel, the battery is connected across each parallel element and the potential difference across each element is the same.

Qualitative investigations of electric circuits

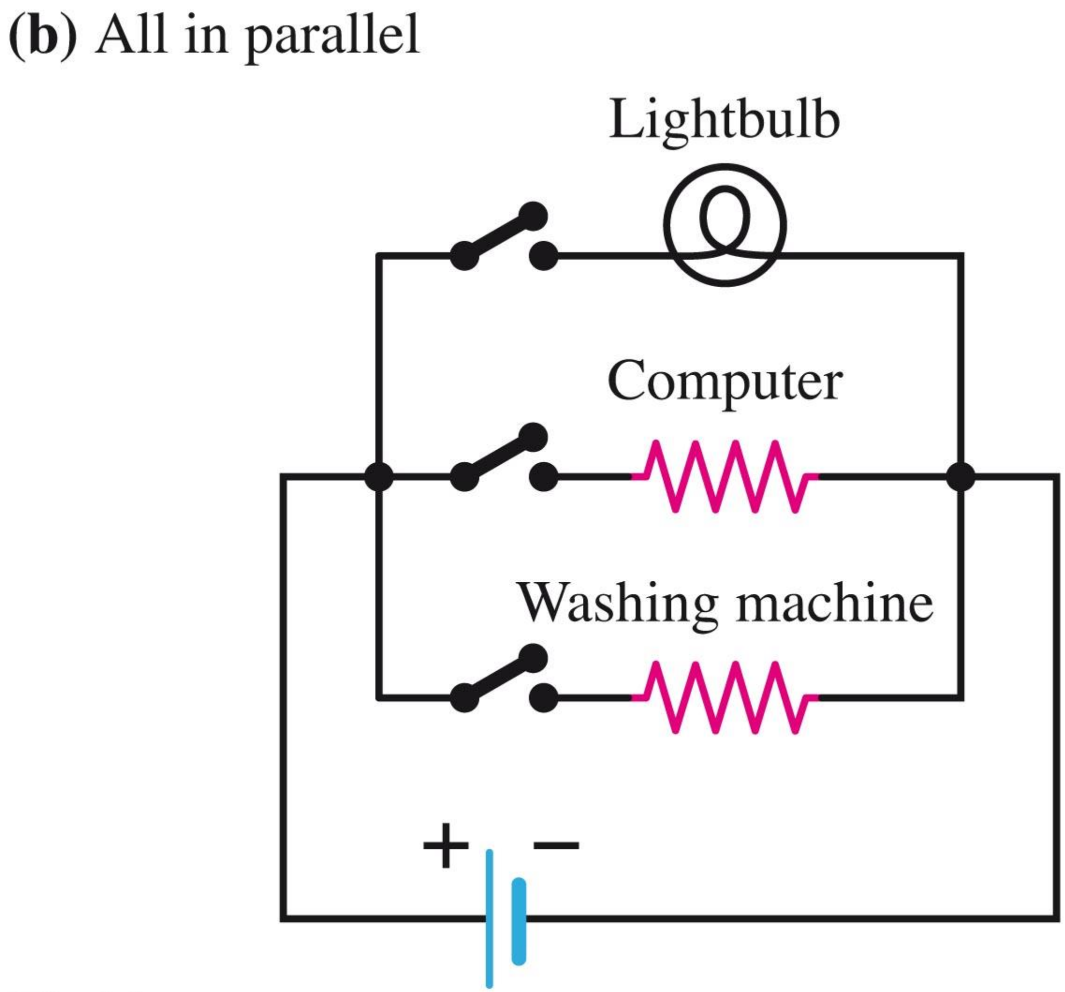
- Adding more circuit elements in series decreases the total current through all the elements and increases the effective total resistance of the elements.
- Adding more elements in parallel increases the total current through the parallel elements and reduces the effective total resistance of the elements.

Qualitative investigations of electric circuits

- The battery is not a source of constant current: it drives a smaller current through circuit elements arranged in series and a larger total current through circuit elements arranged in parallel.
- Changing the number of circuit elements changes the whole circuit. The total current may decrease or increase depending on the arrangement of circuit elements.

How is your house wired?

- Turning any one device on or off will not affect the others.



Joule's law

Joule's law The rate P at which electric potential energy is converted into thermal energy $\Delta U_{\text{thermal}}$ in a resistive device equals the magnitude of the potential difference ΔV across the device multiplied by the current I through the device:

$$P = \left| \frac{\Delta U_{\text{thermal}}}{\Delta t} \right| = I|\Delta V| \qquad (16.4)$$

- Because potential difference and current are related through Ohm's law, Joule's law can be written in two alternate forms:

$$P = I|\Delta V| = I(IR) = I^2R$$

$$P = I|\Delta V| = \left(\frac{\Delta V}{R}\right)|\Delta V| = \frac{(\Delta V)^2}{R}$$

The language of physics: Electricity—charge, current, potential difference, and power

The language of physics: Electricity: charge, current, potential difference, and power

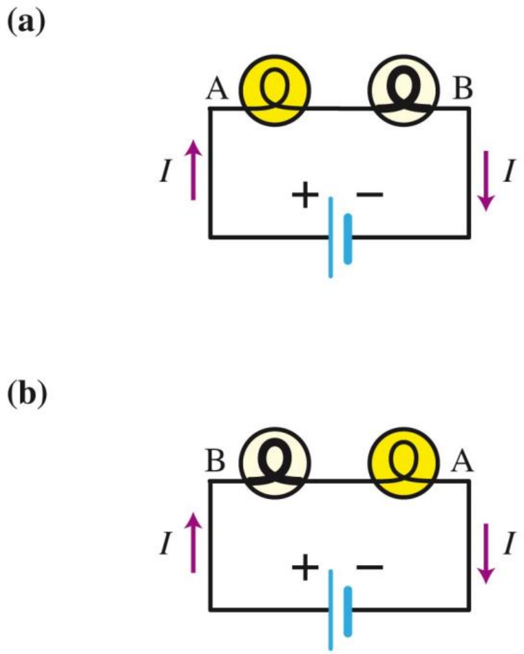
The word "electricity" is used in many ways. People say that electricity flows, that electricity is used to heat buildings, and that electricity comes out of a plug in the wall. When people say that electricity flows, they are referring to the flow of charged particles in wires (electric current); when they talk about heating with electricity, they mean electric potential energy being transformed into thermal energy that heats the environment; and when they talk about wall sockets, they usually refer to a 120-V effective potential difference across any appliance plugged into the socket. When you use the word electricity, make sure you understand which of these ideas you are referring to.

Joule's law

- It is usually most convenient to use:
  - The I^2R expression when comparing power in elements connected in series.
  - The $(\Delta V^2)/R$ expression when elements are connected in parallel.

Joule's law and bulb brightness

- The brightness of a bulb is directly related to its power.
- Two bulbs in series can have different brightness if the resistance of one bulb is greater than the resistance of the other bulb.



Bulb A is brighter than bulb B in both circuits.

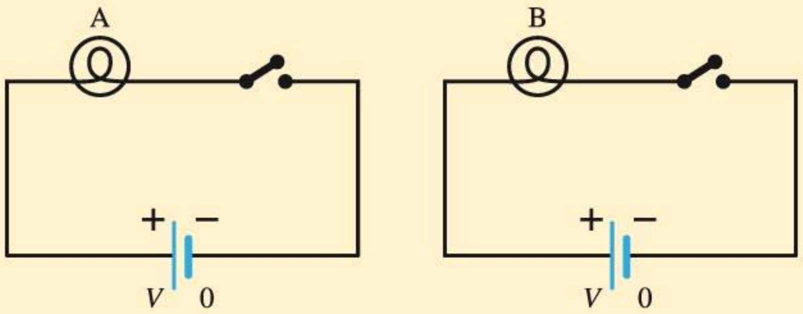
Testing experiment

TESTING EXPERIMENT TABLE

16.7 Predicting the brightness of different bulbs.

VIDEO 16.7

Testing experiment	Prediction	Outcome
Connect bulb A and bulb B to separate identical power supplies with a switch in series in each circuit. Do not close the switches.	The bulbs are now connected across the same potential difference $\Delta V_A = \Delta V_B$. If the power is $P = I\|\Delta V\|$, and $R_A > R_B$, then $I_A < I_B$ and $P_A < P_B$. When we close the switches, lightbulb A should be dimmer than B, but both should be brighter than in the series circuit in Figure 16.22 since the potential difference across each bulb is now higher.	When we close the switches, we observe that bulb A is dimmer than B and both are brighter than when in series in the experiment shown in Figure 16.22.



Conclusion

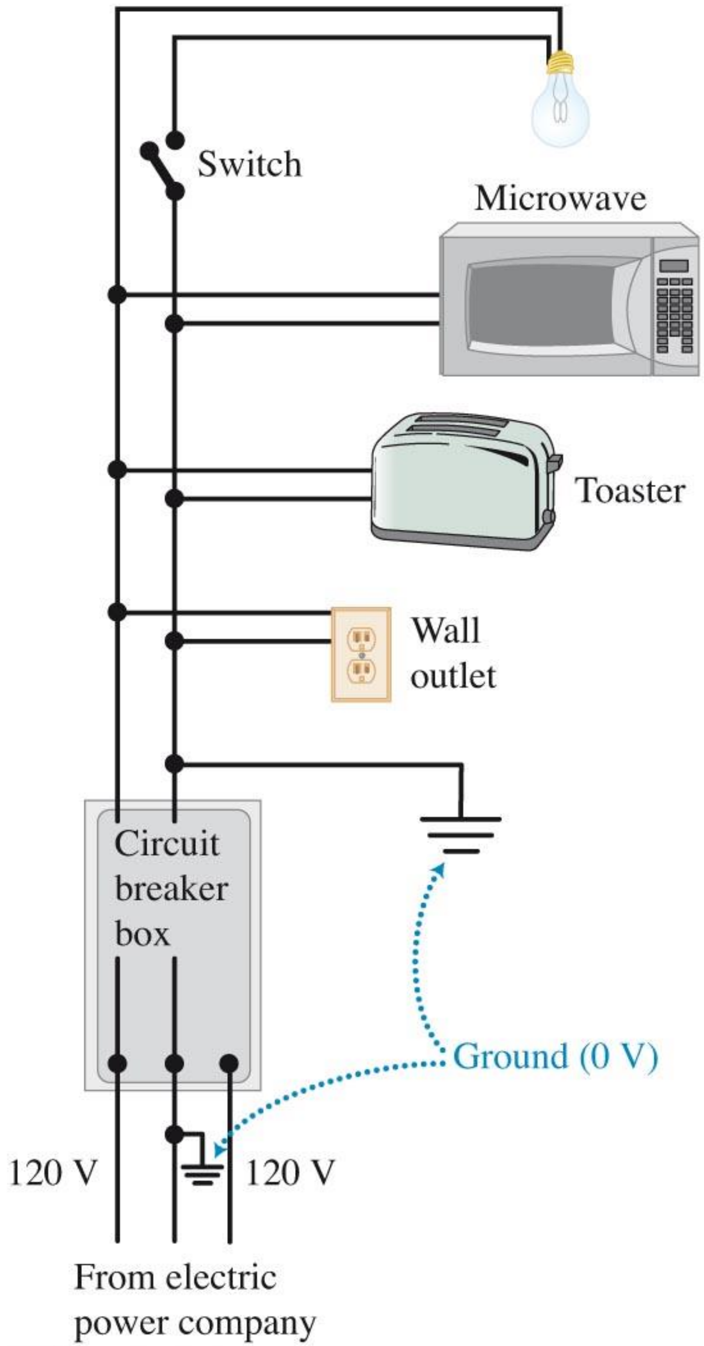
The bulb's brightness depends on the potential difference across it and on the current through it.

Paying for electric energy

- Utility companies do not use the joule. Instead, they use an energy unit called the kilowatt-hour.
- $1\ kW\ h = 3.6 \times 10^6\ J$

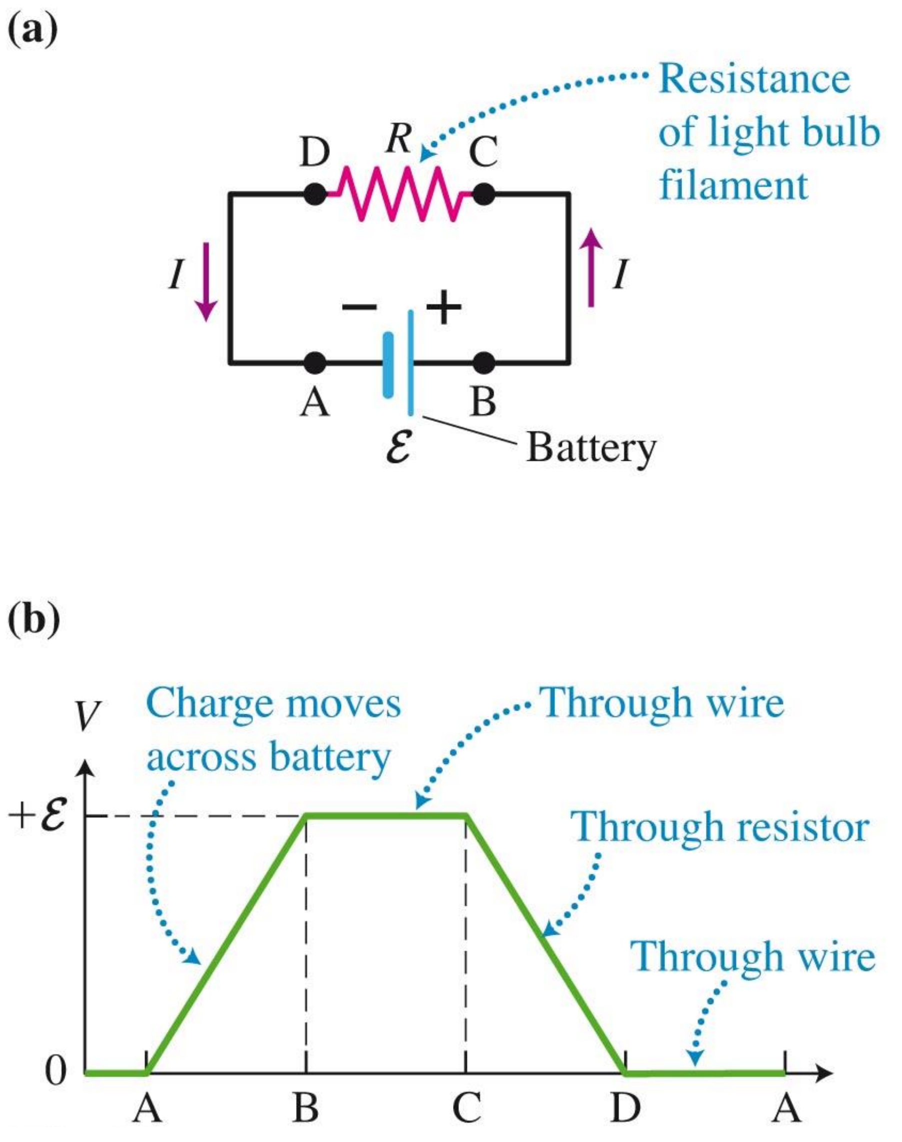
Kirchhoff's rules

- We need techniques to determine the electric current through each circuit element in a complicated circuit.



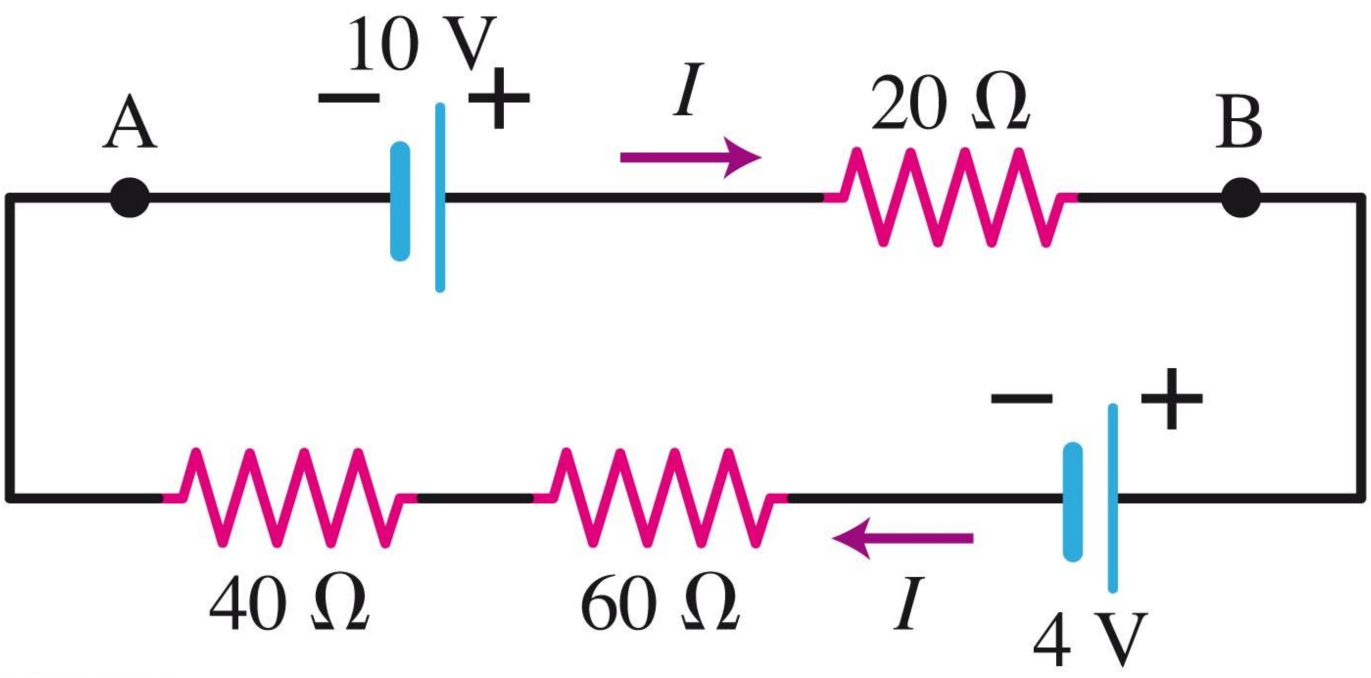
Kirchhoff's loop rule

- Trace the change in electric potential as we move with these charges around the circuit.
- The changes in potential for each step along the trip must add to zero.



Example 16.5

- Use the loop pattern to predict the potential difference between point A and point B in the electric circuit shown in the figure.



Tip

TIP To indicate the signs of the electric potential changes across the resistors in the previous example, we chose and indicated in the circuit drawing the assumed direction of the current. The potential change across a resistor if moving in the direction of the current is $\Delta V = -IR$, and if moving across the resistor opposite the current is $\Delta V = +IR$. We *must* indicate a current direction in the circuit diagram and keep the signs of I and ΔV consistent while making a trip around the circuit.

Kirchhoff's loop rule

Kirchhoff's loop rule The sum of the electric potential differences ΔV across the circuit elements that make up a closed path (called a loop) in a circuit is zero.

$$\sum_{\text{Loop}} \Delta V = 0 \qquad (16.6)$$

Example 16.6

- You buy a 9.0-V battery. To check whether it really produces a 9.0-V potential difference across its terminals, you use a voltmeter and find that it reads 9.0 V. Satisfied, you build a simple series circuit with a 5.0-ohm resistor. An ammeter indicates a 1.5-A current through the resistor. A voltmeter reads 7.5 V across the battery and –7.5 V across the resistor.
  1. Explain why the measurements are unexpected.
  2. What are possible reasons for the discrepancy between the expected and actual results?

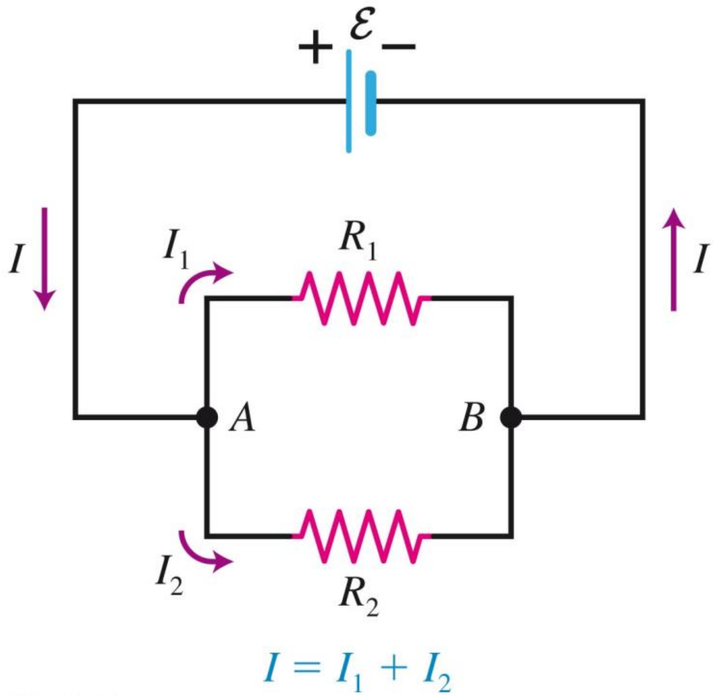
Internal resistance of a battery

- The potential difference across a battery in an open circuit will be greater than that across the same battery in a closed circuit.
  – This is due to internal resistance of the battery.
  – The idea of internal resistance is consistent with observations that batteries feel warm to the touch after they have been operating for a while.

TIP If $r << R$, then $\Delta V_{batt} \approx \varepsilon$.

Kirchhoff's junction rule

- Charged particles making up a current cannot vanish or be created out of nothing (electric charge is a conserved quantity).
- The sum of the currents into a junction must equal the sum of the currents out of the junction.



Kirchhoff's junction rule

Kirchhoff's junction rule The total rate at which electric charge enters a junction equals the total rate at which electric charge leaves the junction:

$$\text{Sum of currents into junction} = \text{Sum of currents out}$$

In symbols:

$$\sum_{\text{In}} I = \sum_{\text{Out}} I \qquad (16.7)$$

Sign conventions for circuit analysis

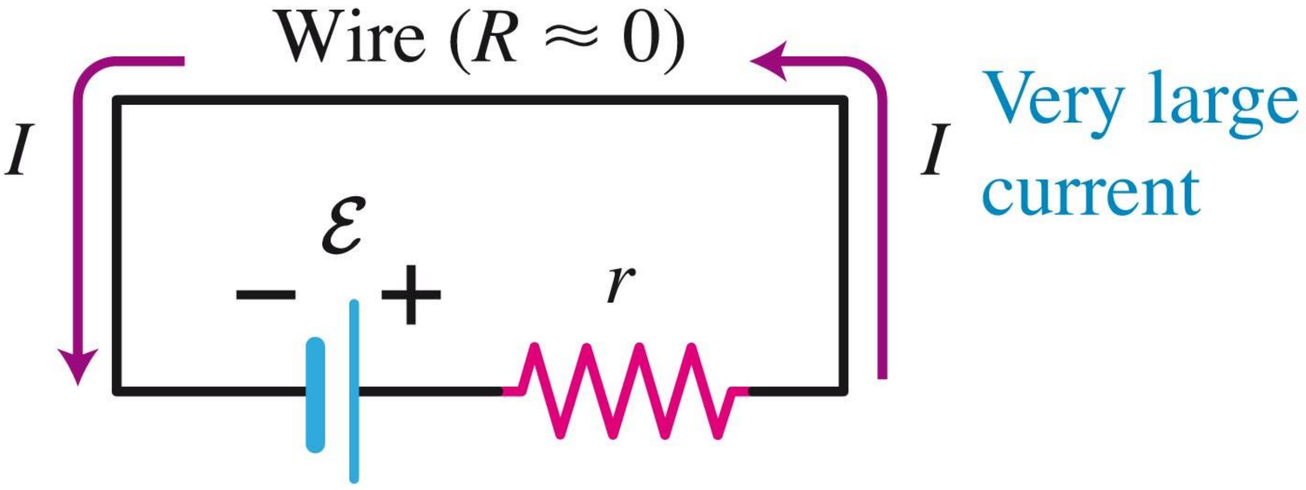
Sign conventions

When using the loop rule for a closed circuit, follow these sign conventions:

- The potential difference across a resistor is $-IR$ when the loop traverses the resistor in the direction of the current through it and $+IR$ when the loop traverses the resistor in the direction opposite the current through it.
- The potential difference across a battery (assuming zero internal resistance) is $+\varepsilon$ when the loop traverses the battery from its negative terminal to its positive terminal and $-\varepsilon$ when the loop traverses the battery from its positive terminal to its negative terminal. The potential difference instead is $\pm(\varepsilon - Ir)$ if the battery's internal resistance cannot be neglected.
- Assuming the resistance of a connecting wire is zero, all points along that wire are at the same potential.

Short circuit

- Imagine that you accidentally connect the terminals of a battery with a connecting wire of approximately zero resistance.



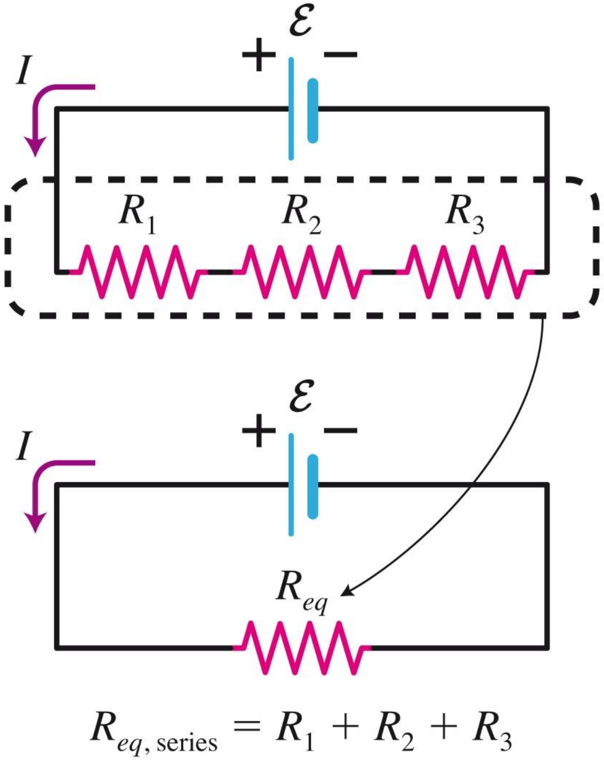
- The wire and the battery become very hot because the current becomes very large.

Series resistance

Series resistance When resistors are connected in series,

- The current through each resistor is the same: $I_1 = I_2 = I_3 = \ldots$
- The potential difference across each resistor is $\Delta V_1 = IR_1, \Delta V_2 = IR_2, \ldots$
- The potential difference across the entire series arrangement of resistors is $\Delta V = \Delta V_1 + \Delta V_2 + \Delta V_3 + \ldots$
- The equivalent resistance of the resistors arranged in series is the sum of the resistances of the individual resistors:

$$R_{eq,\text{ series}} = R_1 + R_2 + R_3 + \ldots \quad (16.8)$$



Parallel resistance

Parallel resistance When resistors are connected in parallel,

- The potential difference across each individual resistor is the same:

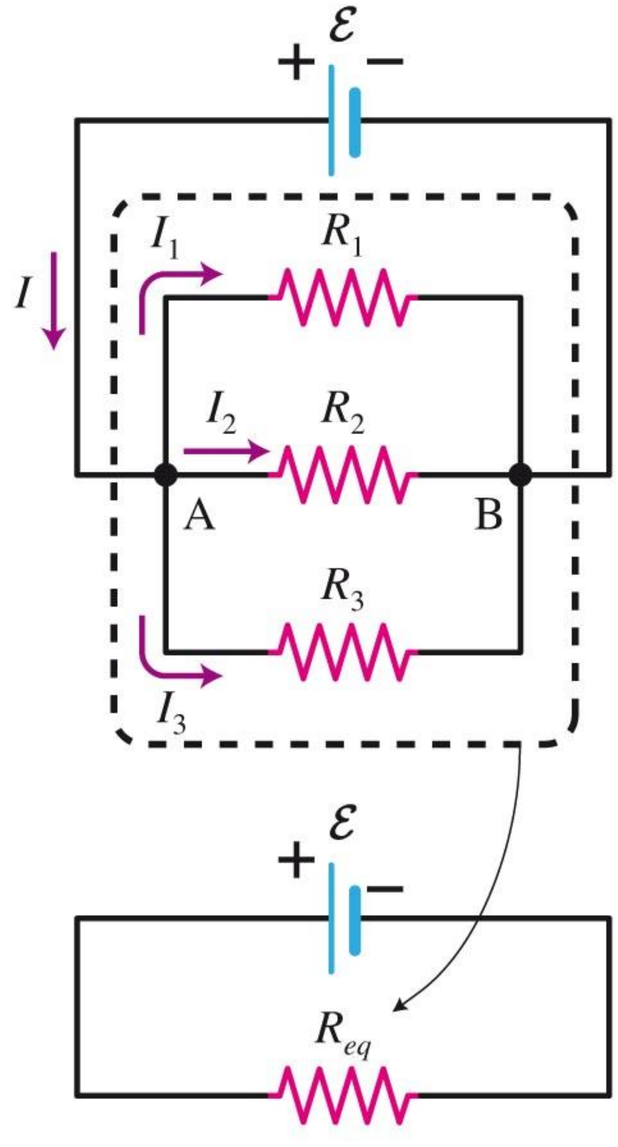
$$\Delta V_1 = \Delta V_2 = \Delta V_3 = \Delta V$$

- The sum of the currents through them equals the total current through the parallel arrangement:

$$I = I_1 + I_2 + I_3 = \frac{\Delta V}{R_1} + \frac{\Delta V}{R_2} + \frac{\Delta V}{R_3}$$

- The equivalent resistance of resistors in parallel is

$$R_{eq,\,\text{parallel}} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots\right)^{-1} \qquad (16.9)$$



$$R_{eq,\parallel} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)^{-1}$$

$$I = I_1 + I_2 + I_3$$

Tip

TIP Do not forget the (−1) exponent when you calculate the equivalent resistance of resistors in parallel.

Example 16.7

- Assume that we have a battery and two identical lightbulbs, each of resistance *R*. We connect the bulbs to the battery in three different configurations: (a) one bulb, (b) two bulbs in series, and (c) two bulbs in parallel.
  1. Determine the equivalent resistance of a single resistor that will produce the same current through the battery as produced in arrangements (b) and (c).
  2. Compare the total power output of the bulbs in arrangements (b) and (c) with the output in (a).

Applying Kirchhoff's rules in the problem-solving strategy: Sketch and translate

- Draw the electric circuit described in the problem statement and label all the known quantities.
- Decide which resistors are in series with each other and which are in parallel.

Applying Kirchhoff's rules in the problem-solving strategy: Simplify and diagram

- Decide whether you can neglect the internal resistance of the battery and the resistance of the connecting wires.
- Draw an arrow representing the direction of the electric current in each branch of the circuit.

Applying Kirchhoff's rules in the problem-solving strategy: Represent mathematically

- If possible, replace combinations of resistors with equivalent resistors.
- Apply the loop rule for the potential changes as you move around one or more different loops of the circuit. Each additional loop you choose must include at least one branch of the circuit that you have not yet included.

Applying Kirchhoff's rules in the problem-solving strategy: Represent mathematically

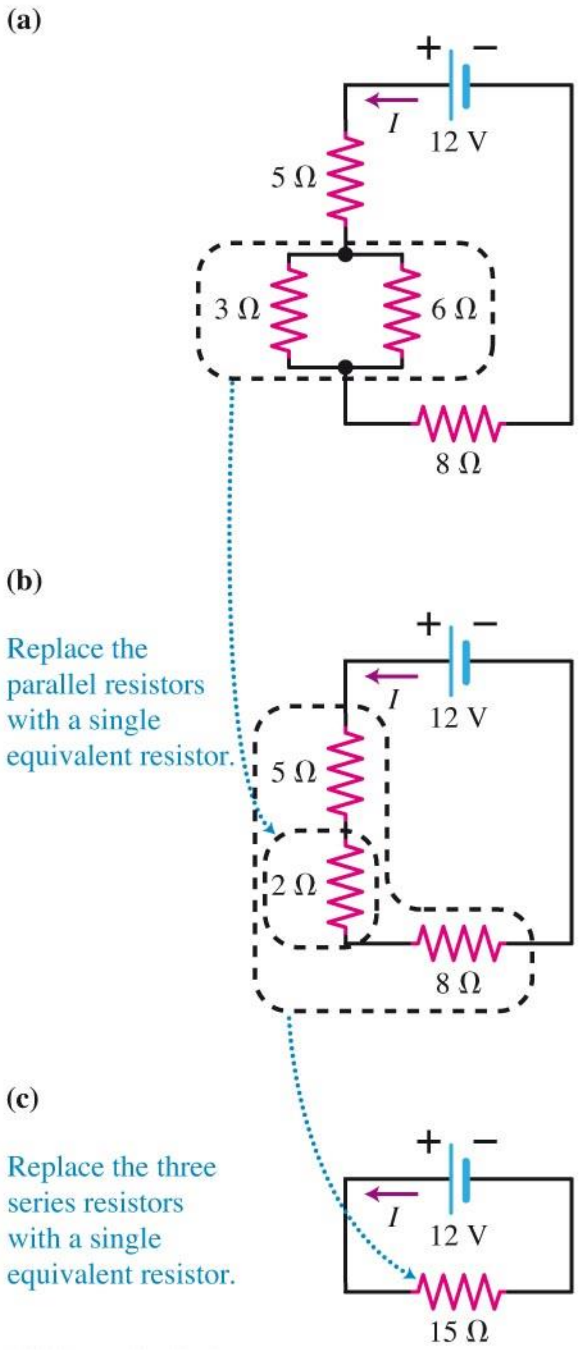
- Once you have included branches, apply the junction rule for one or more junctions. In total, you will need the same number of independent equations as the number of unknown currents.
- If necessary, use expressions for electric power.

Applying Kirchhoff's rules in the problem-solving strategy: Solve and evaluate

- Solve the equations for the unknown quantities. Check whether the directions of the current and the magnitude of the quantities make sense.

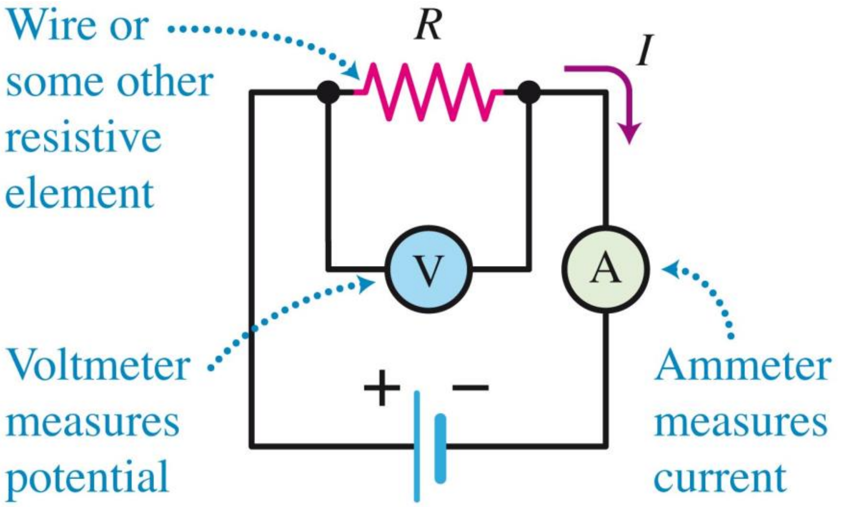
Example 16.9

- Determine the total current *I* through the battery in the figure.



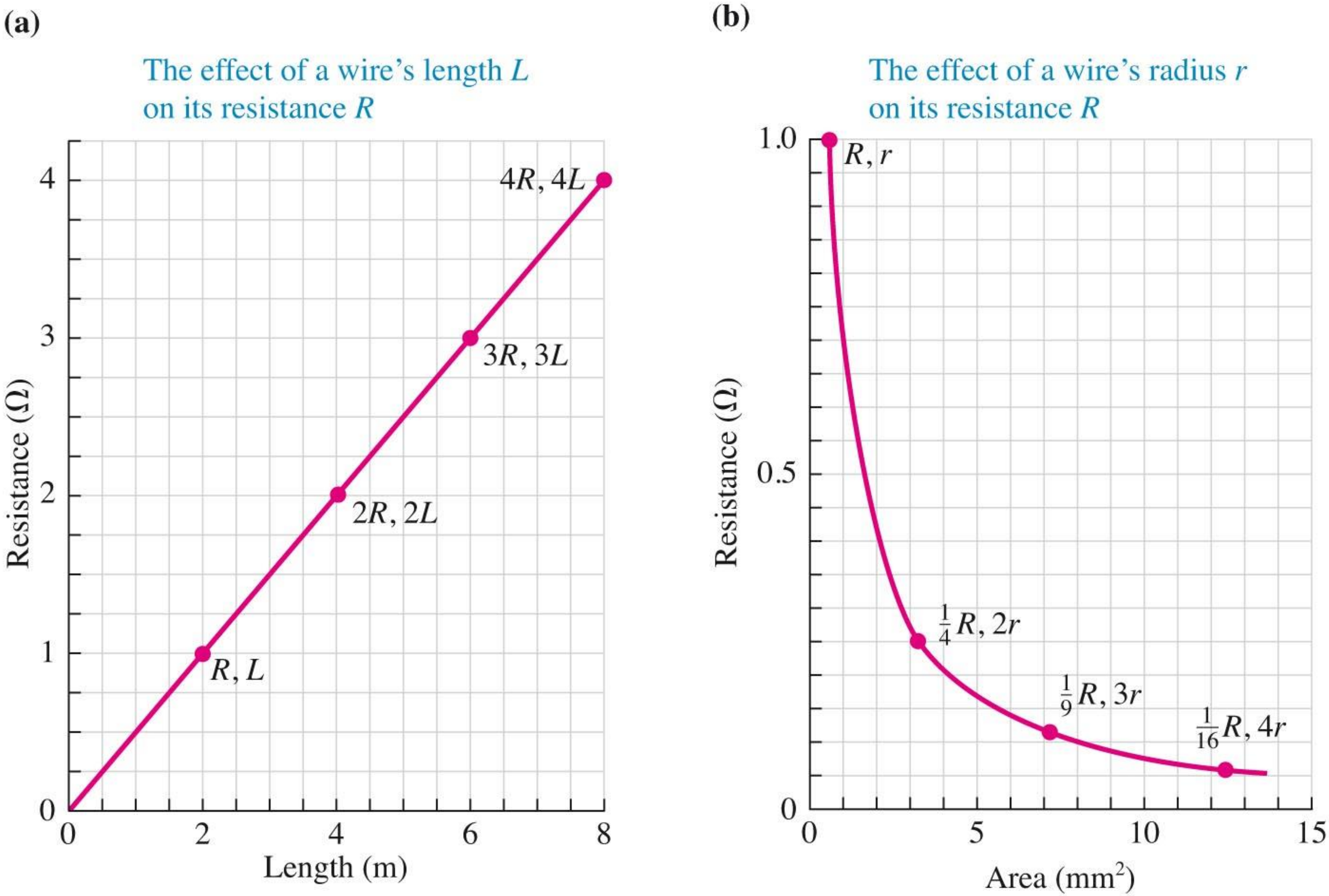
Properties of resistors

- The length and the cross-sectional area of a wire will affect its electrical resistance.
- If a resistor is made of a dielectric material, then the current through it will be nearly zero, so resistance must also depend on the internal properties of the material of which it is made.



$$R = \frac{\Delta V}{I}$$

Properties of resistors



Properties of resistors

- Resistivity ρ of a material characterizes the dependence of the resistance R on the type of material.
- Microscopically, a material's resistivity depends on:
  - The number of free electrons per atom in the material
  - The degree of "difficulty" the electrons have in moving through the material due to their interactions with it
  - Other factors

Resistivity

Table 16.8 **The resistivity ρ of different materials.**

Material	Resistivity ($\Omega \cdot m$, at 20 °C)
Metals	
Silver	1.6×10^{-8}
Copper	1.7×10^{-8}
Aluminum	2.8×10^{-8}
Tungsten	5.2×10^{-8}
Constantan	50×10^{-8}
Dielectrics	
Ordinary glass	9×10^{11}
Hard rubber	1×10^{16}
Shellac	1×10^{14}
Dry wood	10^{14}–10^{16}
Human tissue	
Blood	1.5
Lung tissue	20
Fat	25
Trunk	5
Skin	5000–50,000
Geological materials	
Igneous rocks	10^{2}–10^{7}
Sedimentary rocks	1–10^{5}
Ground water	≈ 10

Electrical resistance

Electrical resistance The electrical resistance R of a resistive circuit element depends on its geometric structure (its length L and cross-sectional area A) and on the resistivity ρ of the material of which it is made:

$$R = \rho \frac{L}{A} \tag{16.10}$$

Tip

TIP **Table 16.8** lists resistivity for materials at a particular temperature. As we know, the resistance of a lightbulb is greater when it is hot than when cold; its resistivity changes with temperature. The resistivity of some other materials, such as constantan, does not change much with temperature.

TIP The Greek letter ρ is used to designate resistivity as well as the density of a substance. Do not confuse the two!

Quantitative Exercise 16.10

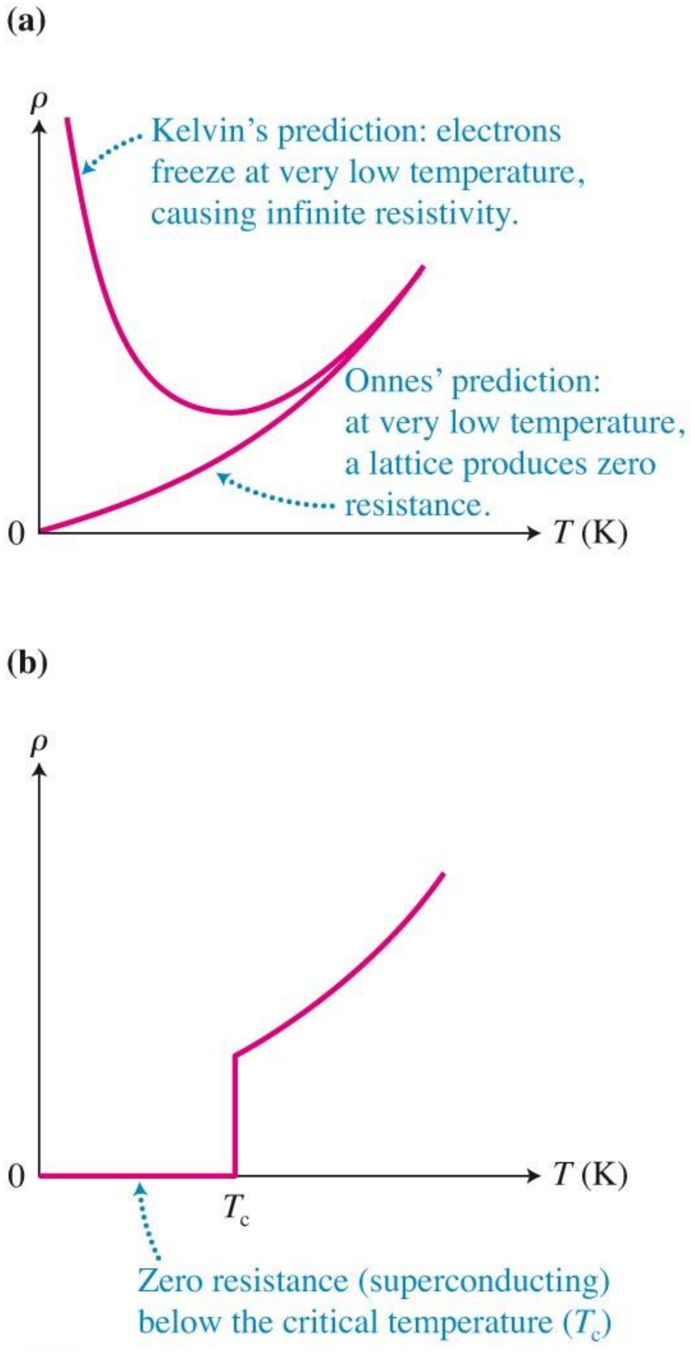
- The connecting wires that we use in electric circuit experiments are usually made of copper. What is the resistance of a 10-cm-long piece of copper connecting wire that has a diameter of 2.0 mm = 2.0×10^{-3} m?

Microscopic model of resistivity

- Free electrons move chaotically inside a metal, and they collide with metal ions.
  - These collisions increase the internal energy of the metal ions, causing them to vibrate more vigorously.
  - The vibrating ions become even more of an obstacle for the electrons.
- This explains why a hotter metal has a higher resistivity than a cooler one and why the resistance of the lightbulb filament increases with temperature.

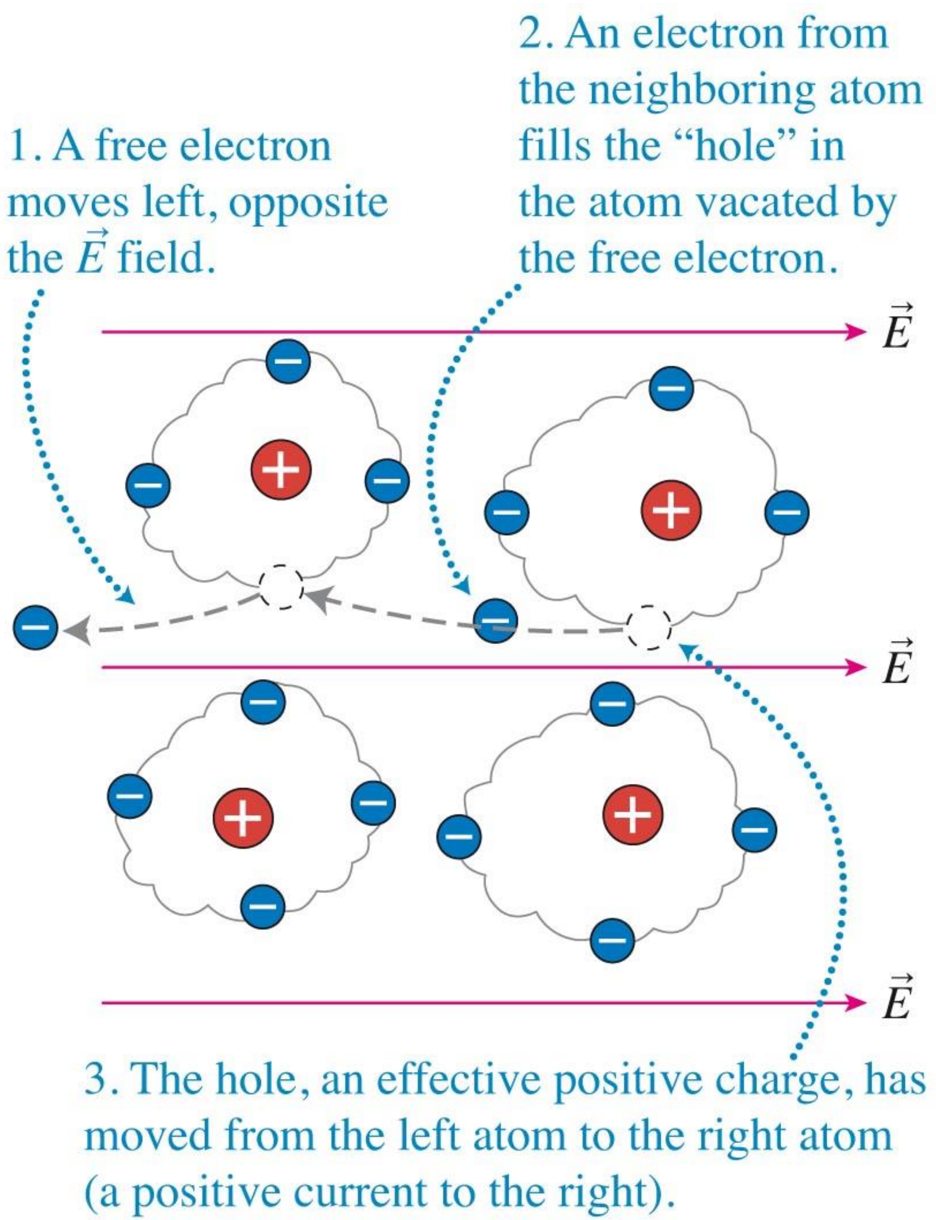
Superconductivity

- At very low temperatures, the electrons no longer transfer energy to the metal lattice ions, so the electrons move through the lattice with exactly zero resistance.



Semiconductors

- The electrical resistance of a semiconductor decreases with increasing temperature.



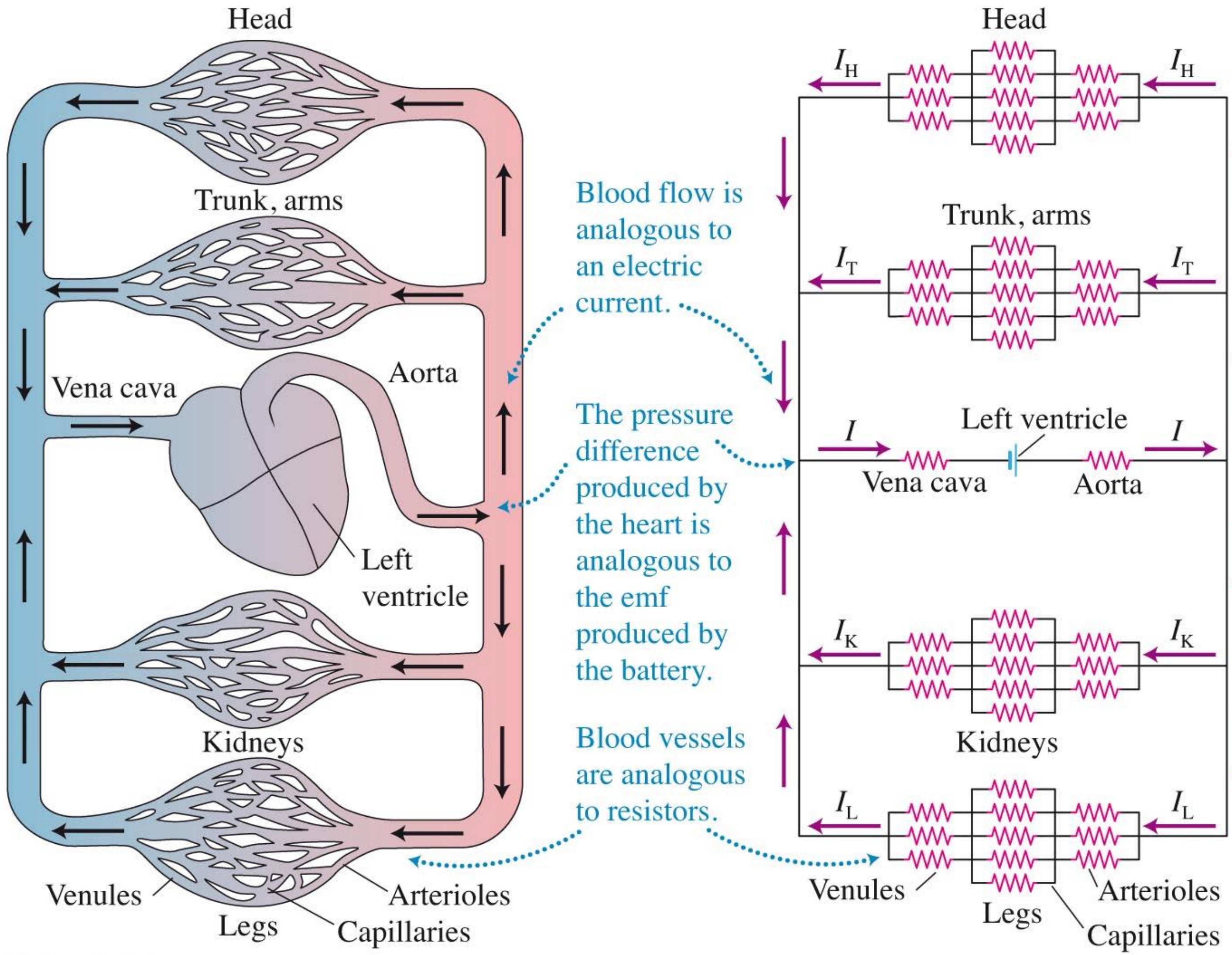
Electrolytes

- Electrolytes are substances containing free ions that make the substance electrically conductive.
- Several electrolytes are critical in human physiology.
- In nerve cells, Na^+, Cl^-, and other ions move across nerve membranes, transmitting electrical signals from the brain to other parts of the body—to activate muscles, for example.

Modeling the human circulatory system as an electric circuit

- Many biological processes can be modeled using ideas of electric circuits.
  - The pressure difference produced by the heart is analogous to the emf produced by a battery.
  - The flowing blood is analogous to a flowing electric charge.
  - The blood vessels, which resist blood flow, are analogous to the electric circuit.

Modeling the human circulatory system as an electric circuit



Circuit breakers and fuses

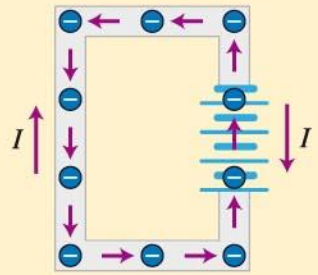
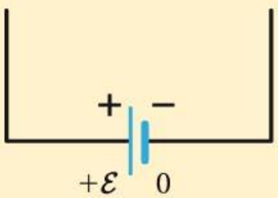
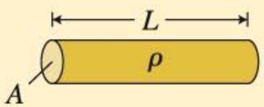
- To prevent overheating in circuits that might cause fires, electrical systems in buildings are installed with circuit interrupters, either fuses or circuit breakers.
  - A fuse is a piece of wire made of an alloy of lead and tin that melts at a relatively low temperature.
  - When the current in a circuit increases to a critical value, a circuit breaker opens a switch, cutting off the current.

Quantitative Exercise 16.12

- A 1380-W electric heater, a 180-W computer, a 120-W lightbulb, and a 1200-W microwave are all plugged into wall sockets in the same part of a house. When the current through the main line exceeds 20 A, the circuit breaker opens the circuit. Will the circuit breaker open the circuit if all these appliances are in operation at the same time?

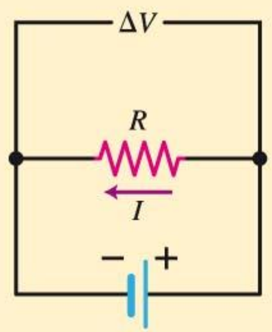
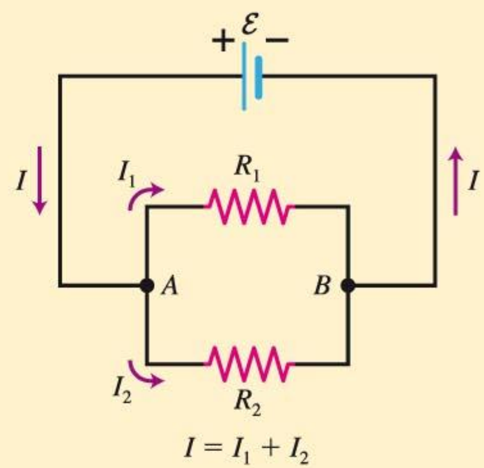
Summary

Summary

Words	Pictorial and physical representations	Mathematical representation
Electric current Electric current I equals the electric charge Q that passes through a cross section of a circuit element divided by the time interval Δt for that amount of charge to pass. (Section 16.1)		$I = \frac{\lvert Q \rvert}{\Delta t}$ Eq. (16.1) Unit: 1 A (ampere) = 1 C/s
Emf The work done per unit charge by a power source (such as a battery) to move charge from one terminal to other. A battery that is not connected to anything has a potential difference ε across its terminals. When there is current in the circuit, the potential difference across the battery may be less than the emf due to internal resistance of the battery. (Sections 16.2 and 16.7)		$\varepsilon = \frac{W}{q}$ Eq. (16.2) Unit: 1 V (volt) = 1 J/C
Electrical resistance The electrical resistance R of a wire depends on its geometrical structure: its length L, cross-sectional area A, and the resistivity of the material ρ. (Section 16.10)		$R = \rho \frac{L}{A}$ Eq. (16.10)

Summary

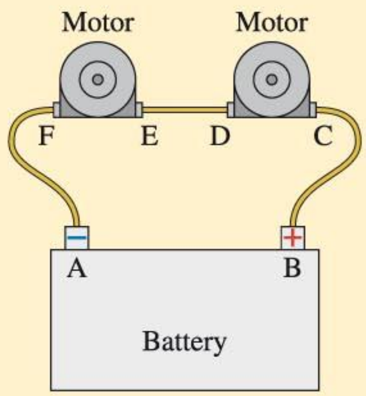
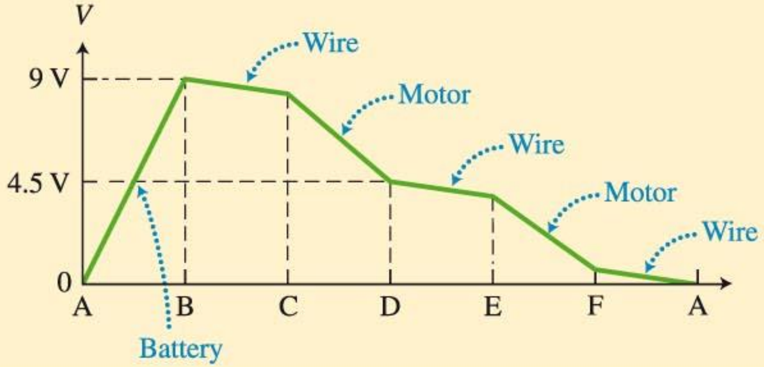
Summary *(Continued)*

Words	Pictorial and physical representations	Mathematical representation
Ohm's law The current I through a circuit element equals the potential difference ΔV across it divided by its resistance R. For ohmic devices, the resistance is independent of the current through the resistor. (Section 16.4) **Joule's law** determines the rate of conversion of electric potential energy into other forms of energy. (Section 16.6)		$I = \dfrac{\Delta V}{R}$ Eq. (16.3) $P = \left\lvert \dfrac{\Delta U}{\Delta t} \right\rvert = I\lvert \Delta V \rvert$ Eq. (16.4) $= I^2R = (\Delta V)^2/R$ Eq. (16.5) Unit: 1 W (watt) = 1 J/s
Kirchhoff's junction rule The algebraic sum of all currents into a junction in a circuit equals the algebraic sum of the currents out of the junction. (Section 16.7)		$\sum_{\text{in}} I = \sum_{\text{out}} I$ Eq. (16.7)

(a)

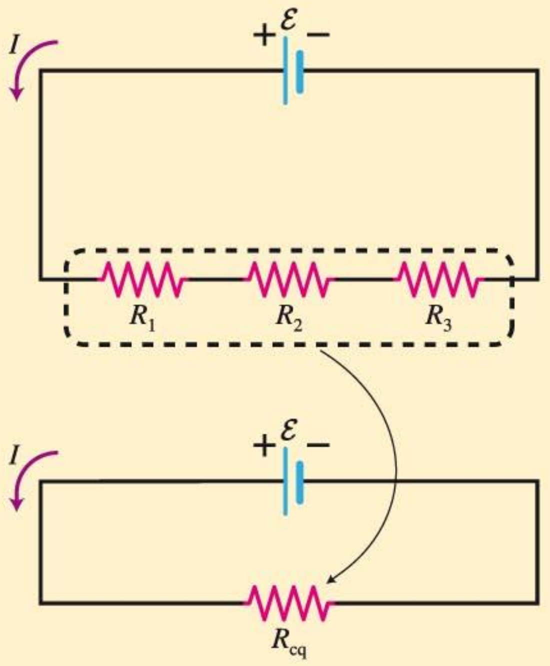
Summary

Summary *(Continued)*

Words	Pictorial and physical representations	Mathematical representation
Kirchhoff's loop rule The algebraic sum of the potential differences across circuit elements around any closed circuit loop is zero. For resistors, the potential difference is $-IR$ if moving across the resistor in the direction of the current and $+IR$ if moving across the resistor opposite the direction of current. For batteries (assuming no internal resistance) the potential difference is $+\varepsilon$ if moving from the negative terminal to the positive terminal and $-\varepsilon$ if moving from positive to negative. (Section 16.7)	(a)  (b) 	$\sum_{\text{loop}} \Delta V = 0$ Eq. (16.6) *Battery:* $\Delta V = \pm\varepsilon$, assuming no internal resistance *Resistor:* $\Delta V = \pm IR$ (including the internal resistance of the battery Ir)

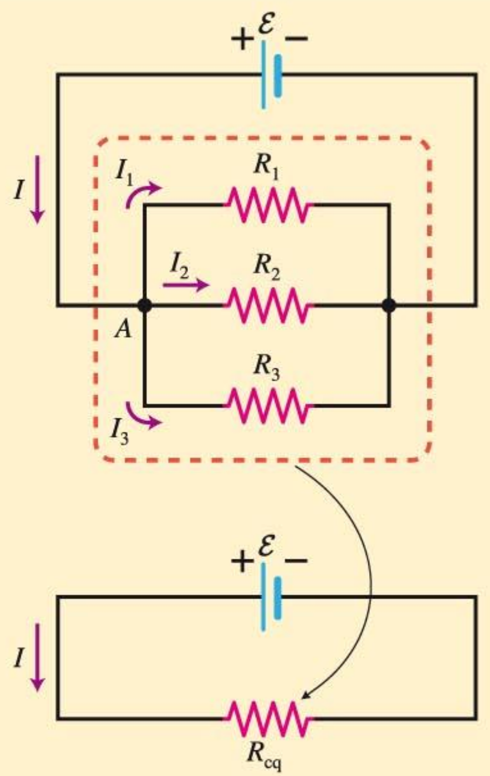
Summary

Summary *(Continued)*

Words	Pictorial and physical representations	Mathematical representation
Series resistance When resistors are connected in series, the current through each resistor is the same. The potential difference across each resistor can differ. The equivalent resistance is the sum of individual resistances. (Section 16.8)		$I_1 = I_2 = I_3 = \ldots$ $R_{eq,\ series} = R_1 + R_2 + R_3 + \ldots$ Eq. (16.8)

Summary

Summary *(Continued)*

Words	Pictorial and physical representations	Mathematical representation
Parallel resistance The potential difference across each resistor is the same. The total current through the parallel resistors is the sum of the currents through each. The total equivalent resistance of resistors in parallel is smaller than the resistance of each individual resistor. (Section 16.8)		$\Delta V_1 = \Delta V_2 = \Delta V_3 = \ \ldots$ $I = I_1 + I_2 + I_3 + \ \ldots$ $R_{\text{eq, parallel}} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ \ldots\right)^{-1}$ Eq. (16.9)